Applications Systems Verification and Transfer Project

Volume VIII: Satellite Snow Mapping and Runoff Prediction Handbook

Clinton J. Bowley,
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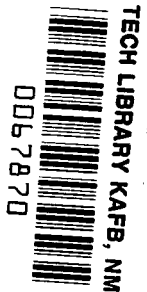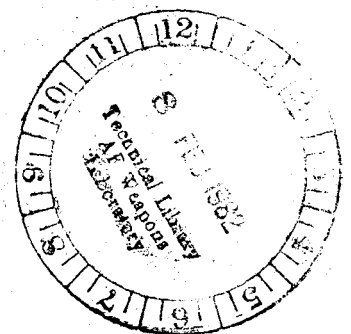
NASA

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Volume VIII: Satellite Snow Mapping and Runoff Prediction Handbook

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ABSTRACT

This handbook has been prepared as one of the reports of
the NASA Applications Systems Verification and Transfer
(ASVT) program. The purpose of the handbook is to update
the various snowcover interpretation techniques, document
the snow mapping techniques used in the various ASVT study
areas, and describe the ways snowcover data have been
applied to runoff prediction. Through documentation in
handbook form, the methodology developed in the Snow
Mapping ASVT can be applied to other areas.

The material presented in this handbook, to a large
extent, is derived from the results produced by the study
centers throughout the project. In addition, meeting were
held with the personnel directly responsible for the
project in each of the four test areas; these meetings
were useful for assessing the particular methods adopted
by each of the study areas for application of satellite
data to improved runoff forecasts. To make the handbook
as complete a document as possible, relevant material
presented in an earlier handbook, which was prepared as an
initial task of the ASVT, is repeated. The contents of
the handbook include: a review of the past history of
satellite snowcover mapping; discussion of the satellite
systems most applicable to snowcover analysis, with
emphasis on NOAA VHRR, Landsat and GOES visible band
imagery; identification and description of the four ASVT
test areas; discussion of the various methods used to map
snowcover in each area, stressing photointerpretation
techniques but covering machine processing techniques as
well; discussion of methodology to incorporate areal
snowcover into operational procedures for each test area,
particularly for use in runoff prediction techniques;
presentation of the results of the project for each test
area, including discussion of the problems encountered in
achieving the general objectives; and an updated summary
of satellite systems and sources of data.

CONTENTS

CONTENTS

FIGURES

FIGURES

FIGURES

FIGURES

FOREWORD

SATELLITE SNOW MAPPING AND
RUNOFF PREDICTION HANDBOOK

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INTRODUCTION

Purpose of Handbook

The year 1980 marks the twentieth anniversary of the launch of the first United States weather satellite. It was not long after TIROS-1 returned its first images from space that scientists began to recognize the potential of the earth-orbiting satellite to provide the hydrologist with useful information on snowcover. By the mid 1960's, serious investigations were underway to develop techniques to map snow from satellite images, determine the accuracy with which snow could be mapped, and assess the advantages and limitations of satellite observations.

Following the introduction of improved spacecraft observational systems in the early 1970's, further studies were carried out to demonstrate that remote sensing from space could provide a more cost-effective means for monitoring snowcover. Moreover, these studies provided an indication that snowcovered area, derived either by aerial or satellite surveys, can be employed as an additional parameter in the prediction of snowmelt-derived runoff. The positive research results in both mapping and runoff correlations led to the operational test of the use of remotely sensed snowcovered area for improving snowmelt runoff forecasts in an Applications Systems Verification and Transfer (ASVT) Program. The overall purpose of the ASVT snow program was to provide all the information necessary for a potential user to make effective decisions concerning the implementation of the new remote sensing technology in an operational applications system.

To assist in the planning of the demonstration program, a Handbook of Techniques for Satellite Snow Mapping was prepared (Reference 1). That earlier handbook included discussion of the various satellite systems with application to snow mapping, the techniques to identify and map snow from these data, and the problems inherent in using satellite observations.

Now, at the completion of the ASVT program five years later, a need exists for an updated handbook. The purpose of this handbook is to update the various snowcover interpretation techniques, document the snow mapping techniques used in the various ASVT study areas, and describe the ways snowcover

data have been applied to runoff prediction. Through documentation in handbook form, the methodology developed in the Snow Mapping ASVT can be applied in other areas.

The material presented in this handbook, to a large extent, is derived from the results produced by the study centers throughout the project. In addition, meetings were held with the personnel directly responsible for the project in each of the four test areas; these meetings were useful for assessing the particular methods adopted by each of the study areas for application of satellite data to improved runoff forecasts. To make the handbook as complete a document as possible, relevant material presented in the earlier handbook is repeated.

The contents of the handbook include the following:

- review of the past history of satellite snowcover mapping, and review of the purpose and objectives of the Snow Mapping ASVT Project;

- discussion of the satellite systems most applicable to snow-cover mapping, with emphasis on Landsat, NOAA-VHRR, and GOES visible band imagery;

- identification and description of the four ASVT test areas, including terrain, vegetation, and precipitation characteristics;

- discussion of the various methods used to map snowcover in each area, stressing photointerpretation techniques but covering machine processing techniques as well;

- discussion of methodology to incorporate areal snowcover into operational procedures for each test area, particularly for use in runoff prediction techniques;

- presentation of the results of the project for each test area, including comparison of results derived from satellite data with results derived from other data, and discussion of the problems encountered in achieving the general objectives; and

- updated summary of satellite systems and sources of data, including existing and planned systems.

History of Satellite Snow Mapping

Using images from the very first satellites of the TIROS series, several early investigators showed that areas of snowcover could be delineated from space (References 2, 3, 4, 5 and 6). Despite these studies, however, little operational application of snowcover mapping from satellite photography could be achieved with the earlier data, due in part to the uncertainty of obtaining an observation over a specified region from the TIROS series of satellites.

In the mid 1960's, with satellites beginning to provide daily global coverage, the first extensive research was carried out to assess the operational application of the data (Reference 7). This work led to the preparation of an operational guide, applicable primarily to the Upper Mississippi-Missouri River Basins region (Reference 8). Subsequently, reports were prepared emphasizing satellite surveillance of mountain snow in the western United States (Reference 9). At the same time, in studies using aerial photographs, Leaf (References 10 and 11) found that for each of three Colorado watersheds, a functional characteristic existed between extent of snowcover during the melt season and accumulated runoff, and that snowcover depletion relationships were useful for determining both the approximate timing and the magnitude of seasonal snowmelt peaks. This research would provide the basis for later studies to relate satellite snowcover area to snowmelt runoff.

In the early 1970's, the second generation of operational meteorological satellites and the first Earth Resources Technology Satellite (ERTS, known later as Landsat) were introduced. An excellent summary report on the status of satellite snow mapping at the time of the introduction of these new observational systems was prepared by an international committee for the World Meteorological Organization (Reference 13). Several researchers then began investigations to evaluate the application to snow hydrology of the improved data from the NOAA VHRR (Very High Resolution Radiometer) and Landsat (References 13, 14, 15, 16 and 17).

In addition to the above studies, which were directed primarily toward the detection and mapping of snow, efforts were underway to relate satellite-derived snowcover area to the resulting snowmelt-produced streamflow. A summary of these studies is given in a document by Rango (Reference 18) describing applications of remote sensing to watershed management. It was the encouraging results of the research efforts using the NOAA VHRR and Landsat data that led to the Snow Mapping ASVT Program. To assist those participating in the ASVT, a Handbook of Techniques for Satellite Snow Mapping was prepared (Reference 1). As one of the initial projects following implementation of the ASVT program, a workshop on "Operational Applications of Satellite Snowcover Observations" was held at South Lake Tahoe, California, in August 1975. The proceedings of the workshop, edited by Rango (Reference 19), contains 28 papers covering photointerpretation and digital techniques used in analyzing Landsat and NOAA satellite data, the use of snowcover observations in streamflow forecasting, and new advances in extraction of snowpack parameters, other than snow extent, employing a variety of remote sensors.

During the period of the Snow ASVT, progress reports have been prepared on a regular basis by each study center. The final reports for each area, summarizing the results of the four-year program, are being published, and a "Final Workshop on Operational Applications of Satellite Snowcover Observations" has been held (Reference 20). In addition to the work directly related to the ASVT, further research results have continued to be reported in recent years (References 21, 22 and 23).

Nearly all of the research that has been carried out, as well as the emphasis in the Snow ASVT, has been directed toward the use of observations in the visible portion of the spectrum from unmanned satellites. Research has also

been carried out, however, using other types of data, including: photography from the Skylab and Apollo-Soyuz manned spacecraft missions (References 24 and 25); thermal infrared data from the NOAA VHRR (Reference 26); near-infrared data from the Nimbus-3 satellite and from the Skylab multispectral scanner (References 27 and 28); and microwave measurements (Reference 29). An investigation is also in progress using thermal infrared data from the Heat Capacity Mapping Mission (HCMM).

Description of Snow Mapping ASVT Program

NASA ASVT programs result from exploratory investigations in the research program that have shown promising conclusions. As a result, when an ASVT is undertaken, most necessary supporting research has already been completed. An ASVT is an integrated test of the capability of a remote sensing based system to accomplish a specific applications objective on an operational basis. To accomplish this, ASVT's directly involve the user community, provide a user oriented assessment of the system, and provide in summary form the information necessary for a potential user to make effective decisions concerning the implementation of the technology in an operational framework. Mandatory products from an ASVT are a documented methodology suitable for widespread distribution, a comprehensive user evaluation of the systems accuracy and reliability, and a complete cost-effectiveness study.

The Operational Applications of Satellite Snowcover Observations (OASSO) project was initiated in July 1974 and formally became part of the NASA ASVT Program in July 1975. Being conducted with the cooperation of nine operational water management agencies in the western United States, the OASSO project was scheduled for completion in 1978.

Day to day management of the OASSO project was conducted at NASA's Goddard Space Flight Center (GSFC) in coordination with NASA/Headquarters. NOAA's National Environmental Satellite Service (NESS) also participated in OASSO by supplying operational NOAA satellite data and supporting analysis work.

The overall purpose of the Snow Mapping ASVT was to perform operational evaluations of total technical capability in cooperation with various operational water management agencies in four test areas: Arizona, California, Colorado and the northwest United States. Each of the four study areas had operational agency personnel working in cooperation with remote sensing specialists to adapt the existing technology to water supply forecasting needs. The objectives of the Snow ASVT in each study area are discussed in detail in the initial workshop proceedings (Reference 19), and the final workshop proceedings (Reference 20).

DESCRIPTION OF SATELLITE SYSTEMS WITH APPLICATION TO OPERATIONAL SNOW MAPPING

Three satellite systems - Landsat, NOAA-VHRR (Very High Resolution Radiometer), and GOES (Geostationary Operational Environmental Satellite) - have application to operational snow mapping. Visible-channel data from these three systems were used to map snowcover area in the Snow ASVT program. These three systems are described in the following sections, and examples of each type of

4

imagery are presented. Other satellite systems that provide visible spectral range data, but do not have application to operational snow mapping, are also described in this section. The application of data in other portions of the spectrum (near-infrared, thermal infrared, and microwave) are discussed in a later section of the handbook. Additional references describing the various sensor systems, as well as information on the availability and sources of the various types of data, are given in Appendix B.

Landsat

High resolution, multispectral data from space first became available in the summer of 1972 with the launch of Landsat-1, called at that time, the Earth Resources Technology Satellite (ERTS). Landsat-2 was placed in operation in January 1975, and Landsat-3 was launched in March 1978. Landsat-1 was deactivated in January 1978 after operating well beyond its originally planned lifetime; as of early 1979, data were being collected by Landsat-2 and Landsat-3.

The Landsat spacecraft are polar orbiting satellites that view the earth from an altitude of approximately 900 km (500 nm). The primary sensor system carried by Landsat is the Multispectral Scanner (MSS). The MSS observes in four spectral bands, ranging from the visible to the near-infrared portions of the spectrum; the four bands are the MSS-4 (green: 0.5 to 0.6 μm), MSS-5 (red: 0.6 to 0.7 μm), MSS-6 (red to near-infrared: 0.7 to 0.8 μm), and MSS-7 (near-infrared: 0.8 to 1.1 μm). Landsat-3 also carries a fifth MSS band, which measures in the thermal infrared portion of the spectrum (10.4 to 12.6 μm). A Landsat MSS-5 image viewing a portion of the Sierra Nevada is shown in Figure 1.

Landsat views an area 185 km (100 nm) wide, and the MSS has a ground resolution of 80 meters (260 feet); features can be mapped accurately from the imagery to a scale of at least 1:250,000. Because of the relatively narrow swath viewed by Landsat, the satellite does not provide repeat coverage each day. In fact, at lower latitudes, the satellite repeats coverage of the same area only once every 18 days. As a result of the overlapping of orbits at higher latitudes, however, coverage of the same area (north of 60°N) can occur on two or three consecutive days during each 18-day repeat cycle of the satellite.

Landsat direct readout coverage of North America is provided by three receiving stations in the United States and two in Canada. The data can be obtained by the user in various formats, primarily 70 mm (scale 1:3 million) and 240 mm (scale 1:1 million) imagery. Color composite imagery processed by combining the different spectral bands and digitized computer tapes can also be obtained. Landsat data are currently available in real-time from the Canadian readout stations on a routine basis, and from the NASA Goddard Space Flight Center for specially approved projects.

The Landsat series of satellites has also carried a second sensor system, the Return Beam Vidicon (RBV). The RBV failed early in the life of Landsat-1, was used very little on Landsat-2, but is routinely acquiring data on Landsat-3. The RBV on Landsat-1 and 2 was a three-camera system, similar to the MSS in spectral response, resolution, and area viewed. The Landsat-3 RBV, however, is a single-channel instrument covering a spectral range of 0.50 to 0.75 μm, and having an improved resolution (about 40 m as compared to the 80 m MSS resolu-

Figure 1.   Landsat-2 MSS-5 image viewing the Lake Tahoe area of the Sierra
            Nevada, 22 April 1978.

6

tion). The RBV images are processed in a 1:250,000 scale format. For continuity with the earlier satellites, the Landsat-3 data used for snow mapping have, nevertheless, been primarily from the MSS sensor. An example of an RBV image, also viewing the Lake Tahoe area, is shown in Figure 2.

NOAA Very High Resolution Radiometer (VHRR)

The NOAA series of environmental satellites was in operation during the period of the snow ASVT. The primary sensor on the NOAA satellites was the VHRR (Very High Resolution Radiometer), a dual-channel radiometer sensitive in the visible (0.6 to 0.7 μm) and thermal infrared (10.5 to 12.5 μm) spectral regions. The VHRR sensor was flown on each of the NOAA satellites from January 1973 until early 1979 (through NOAA-5). The spatial resolution of the VHRR is 900 m (0.5 nm), an order of magnitude poorer than that of Landsat, but still sufficient for mapping snowcover.

The NOAA VHRR is designed primarily for direct readout with three readout stations in use. Repeat coverage is provided twice daily; near local noon (visible and infrared), and again near local midnight (infrared), allowing both rapid and longer term changes in snowcovered area to be monitored. The area that can be covered when the satellite passes directly overhead is a strip about 2,200 km (1,400 nm) wide and more than 5,000 km (3,000 nm) long. The VHRR also has a limited stored data capability; eight minutes of data can be stored on each orbital pass yielding an image about 2,200 km wide and 2,200 km long.

The VHRR imagery is available from the National Environmental Satellite Service in a standard 25 cm by 25 cm format (scale approximately 1:10 million). VHRR data are also available in digitized format and in enhanced imagery that can be processed from the digitized tapes. An example of a NOAA VHRR image, viewing the southwestern United States, is shown in Figure 3.

Effective in early 1979, the NOAA satellite series has been replaced by the TIROS-N satellite series, the third generation of operational meteorological satellites. The primary sensor on TIROS-N is the AVHRR (Advanced VHRR), which has a spatial resolution similar to that of the VHRR, but is a four-channel instrument. For comparison with the VHRR images, an example of a TIROS-N image is shown in Figure 4; this image is the full resolution (1 km) direct readout data, and serves to illustrate the excellent quality of the TIROS-N AVHRR (note that the distortion at the edges of the image is somewhat greater than that of VHRR images because of the lower TIROS-N orbit).

The initial satellite of the series, TIROS-N, was launched in October 1978 and provides a mid-afternoon observation (about 1500 LST). The NOAA-6 satellite, the second of the TIROS-N series, was launched in late June 1979 and provides an early morning observation (about 0730 LST); during mid-winter, therefore, the lack of adequate solar illumination at that hour may preclude useful snowcover observations from NOAA-6.

Geostationary Operational Environmental Satellite (GOES)

A third type of satellite system with application to snow mapping is the GOES
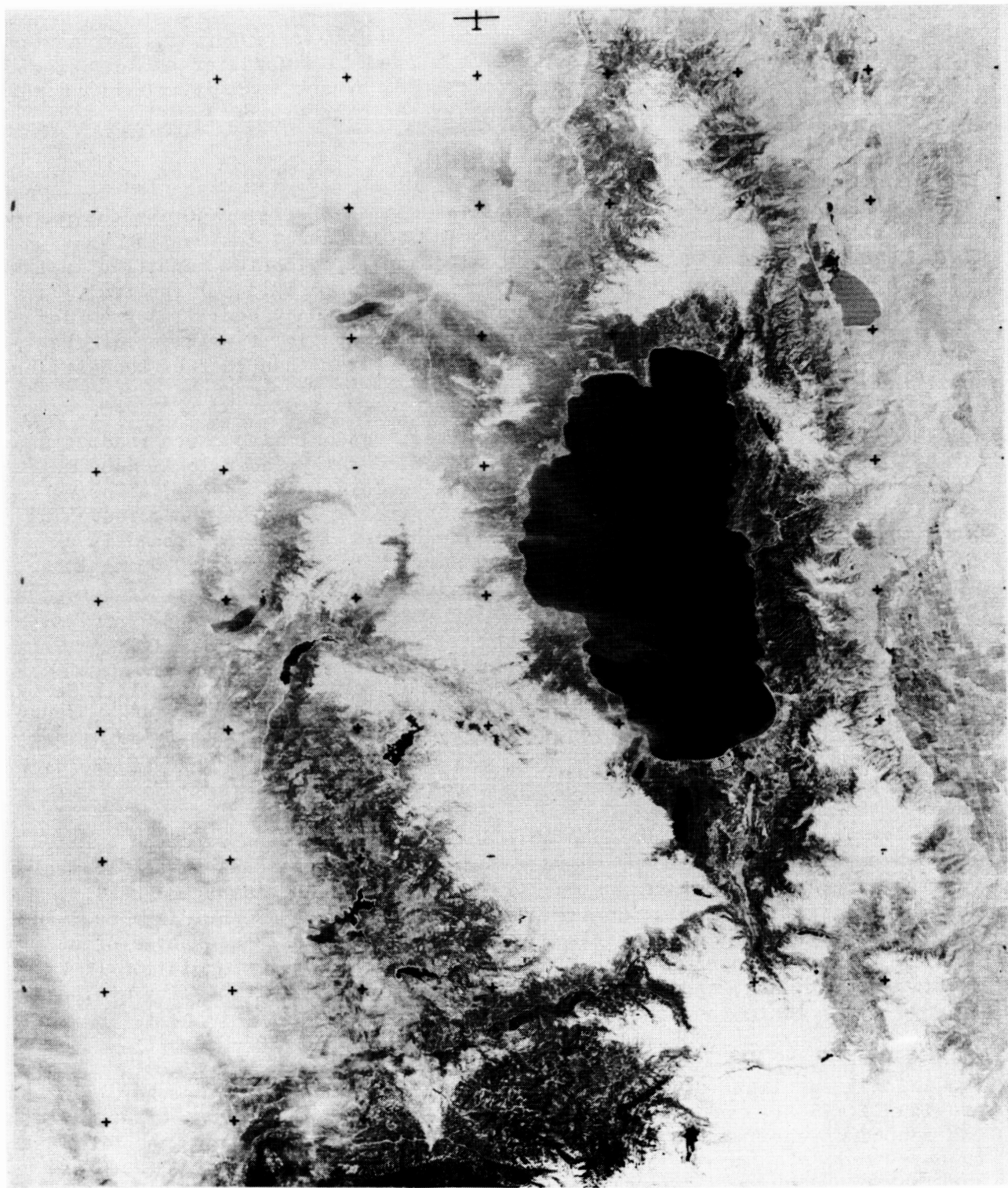
Figure 2.   Landsat-3 RBV image viewing the Lake Tahoe area, 6 June 1978.
            Some cloud obscures the snowcover west of the lake.
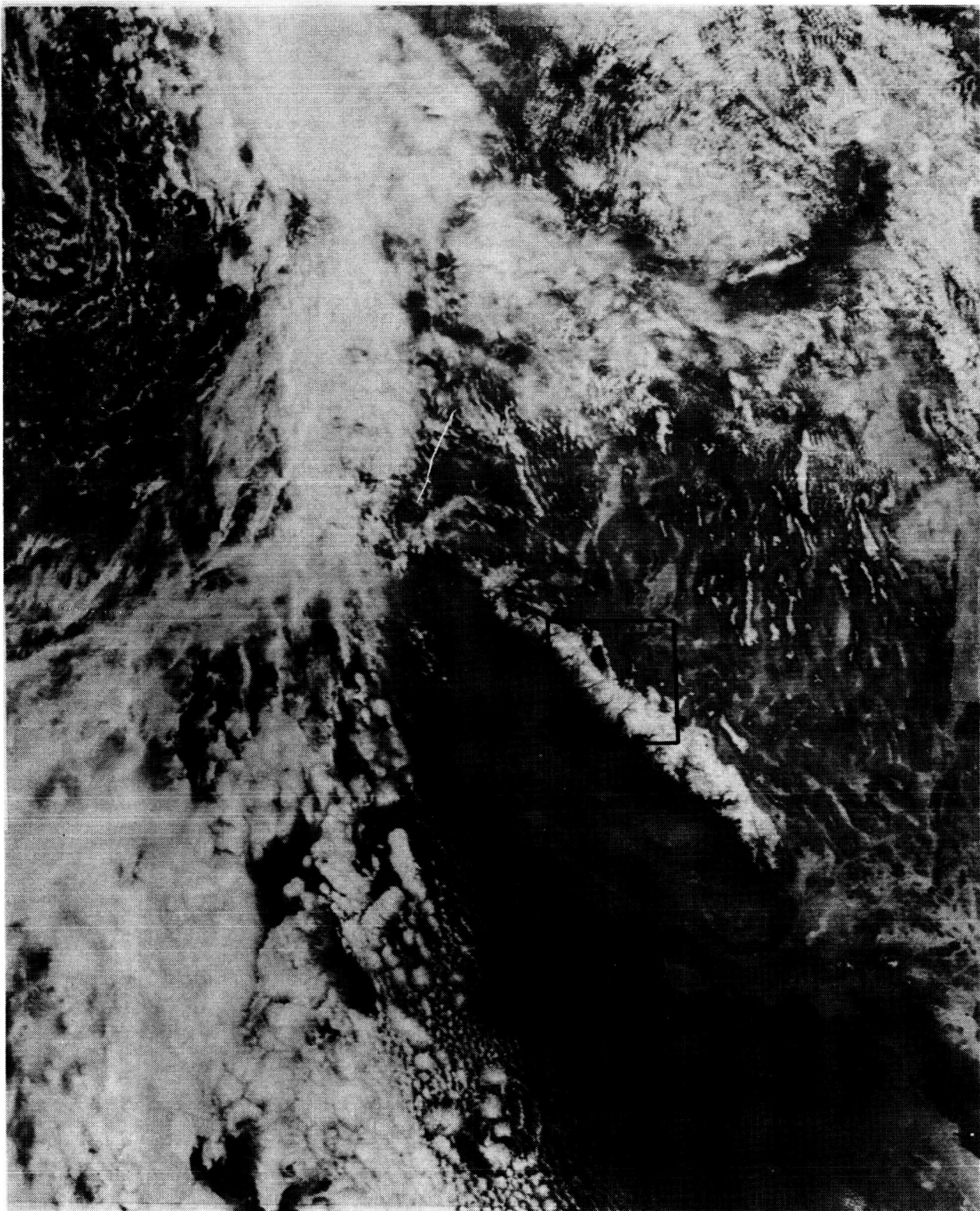
Figure 3.   NOAA VHRR visible-channel image viewing the southwestern United
States, 22 April 1978. The area outlined over the Sierras is the
area of the Landsat MSS-5 scene shown in Figure 1.

Figure 4. An example of TIROS-N visible-channel imagery viewing the north-eastern United States, 17 February 1979.

10

system (Geostationary Operational Environmental Satellite). A geostationary
or so-called geosynchronous, satellite always remains above the same point on
the equator, and it continually views the same portion of the earth. The
required altitude for a satellite to remain in geostationary orbit is 35,903 km.

Following NASA's experimental series of the late 1960's known as ATS (Applica-
tions Technology Satellite), came the GOES satellite program, which was initi-
ally called SMS (Synchronous Meteorological Satellite). The principal sensor
on the GOES is the Visible and Infrared Spin-Scan Radiometer (VISSR), which
provides the capability for acquiring observations every half-hour both day
and night. The visible (0.54 to 0.70 μm) channel provides albedo measurements
between 0.5 and 100 percent, and the infrared (10.5 to 12.5 μm) channel pro-
vides radiance temperature measurements between 180°K and 315°K.

The GOES data can be processed at different resolutions, ranging from 4 km
(full-disc) to 1 km (sectorized) in the visible channel data. The maximum
resolution for the thermal IR data is 8 km. Because the viewing angle of GOES
becomes more oblique as latitude increases, the resolution of the imagery
deteriorates with latitude. Therefore, GOES is more useful for mapping snow
in the more southern areas, such as Arizona and the southern Sierra Nevada.
An example of a GOES image is shown in Figure 5.

Other Satellite Systems with Visual Spectral Range Sensors

Other satellite systems have also provided observations in the visual spectral
range, but do not have application for operational snow mapping because the
data either are not available in real-time or the systems were not designed to
provide repetitive coverage. The satellite systems of interest are described
below.

Defense Meteorological Satellite Program (DMSP)

The Defense Meteorological Satellite Program (DMSP) is under the direction of
the United States Air Force. The resulting DMSP data are made available for
non-military use, but are not archived in an easily retrievable fashion and
are not generally available to the civilian sector in real-time. These data
are, therefore, not useful for snow mapping by the civilian sector, although
regular operational use is made by the Air Force in their global snow mapping
activity.

The DMSP system comprises two satellites, so the data frequency is four times
per day (one satellite passes over at noon and midnight; the other at early
morning and evening). The DMSP satellites carry two-channel radiometers that
are sensitive in similar, but wider, spectral bands than the VHRR; the two
bands are in the visible to near-infrared (0.4 to 1.1 μm) and in the thermal
infrared (8.0 to 13.0 μm). Data can be transmitted at a resolution similar to
that of the full-disc GOES (about 4 km) or at a finer resolution somewhat
better than that of the VHRR (about 0.6 km). An example of a DMSP image is
shown in Figure 6. Of particular interest for snow mapping is that a DMSP
satellite launched during 1979 carries a "snow-cloud discriminator", an instru-
ment with a channel in a near-infrared (1.5 to 1.6 μm) band. The application
of near-infrared data is discussed in a later section.

11
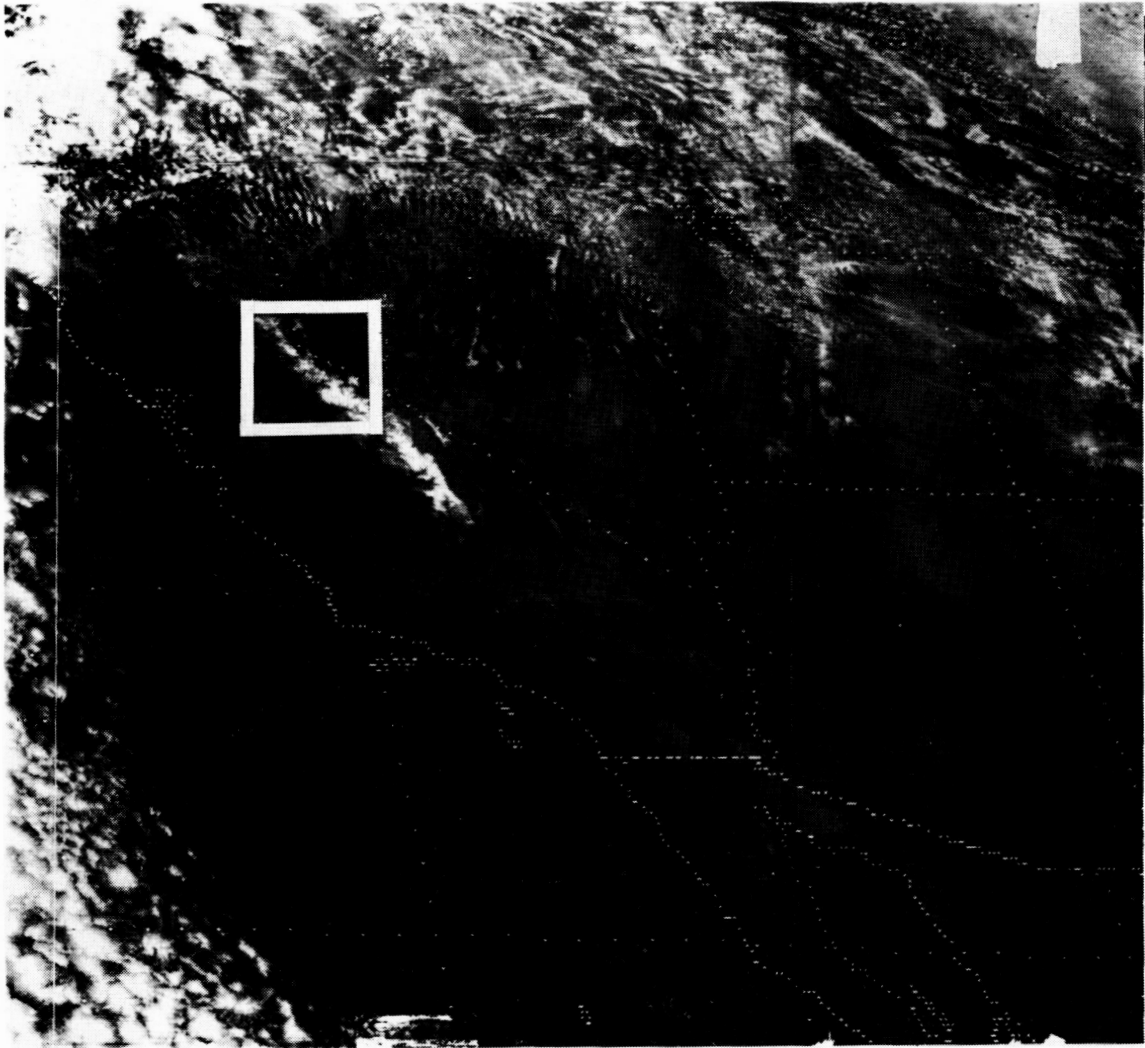
Figure 5. GOES VISSR image viewing the southwestern United States, 22 April 1978. The area outlined over the Sierras is the area of the Landsat MSS-5 scene shown in Figure 1.

12
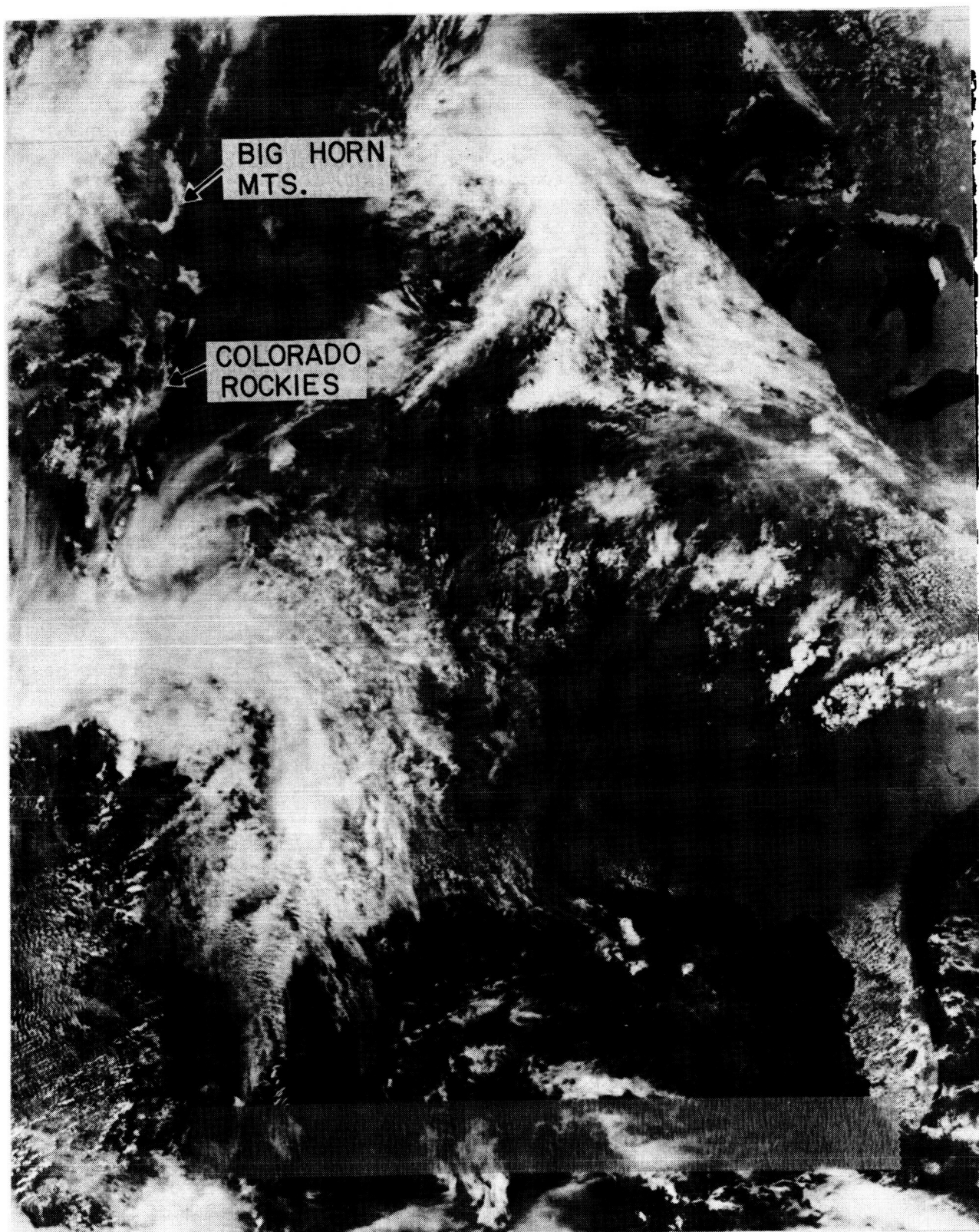
Figure 6.   DMSP visible-channel image viewing a portion of the United States, 14 April 1977.

Heat Capacity Mapping Mission (HCMM)

The Heat Capacity Mapping Mission (HCMM), launched in April 1978, was the first of a planned series of Applications Explorer Missions (AEM) that involve the placement of small spacecraft in special orbits to satisfy mission-unique, data acquisition requirements. The HCMM supports exploratory scientific investigations to establish the feasibility of acquiring thermal infrared remote-sensor derived temperature measurements of the Earth's surface within a 12-hour interval at times when the temperature variation is a maximum, and applying the day/night temperature different measurements to the determination of thermal inertia (that property of material to resist temperature changes as incident energy varies over a daily cycle). The HCMM spacecraft orbit is sun synchronous with a nominal ascending equatorial crossing time of 1400 LST, in order to provide north middle latitude (40 degrees) crossing times of 1330 LST and 0230 LST at 12-hour intervals approximately every five days.

The HCMM radiometer is a two-channel sensor similar to the VHRR in its spectral ranges, but with somewhat better resolution. Although the satellite was designed primarily for its geological applications, snow hydrology studies using the HCMM data are being carried out. An example of a HCMM visible-channel image is shown in Figure 7. The application of the HCMM thermal infrared data to snow hydrology is also discussed in a later section.

Photography from Manned Space Flights (Compared with Landsat and Aerial Photography)

Considerable photography over snowcovered areas within the United States has been collected on manned space flights, especially the Skylab missions, both as part of the EREP (Earth Resources Experiment Package) experiment and the Skylab-4 Visual Observations Project. Although these data were not intended for operational snow mapping use, the cameras did provide photographs with higher resolutions than even the data from Landsat. Examples of Skylab photographs are given to provide a further comparison of snowcover observations at different resolutions. To assist in comparing the different sensor resolutions, aerial photography and a Landsat image are also shown (Figures 8 and 9); the aerial photography, Landsat, and Skylab photography all cover the same portion of the Arizona study area.

Skylab S190A and S190B photographs taken on an EREP pass across central Arizona are shown in Figures 10 and 11, respectively. The S190A is a six-camera multispectral system, with a resolution of 30-70 meters (as compared to 70-100 meters for Landsat and 1 km for VHRR). The photograph shown is in the visible spectral region. The S190B camera has a resolution of 15-30 meters; the photograph shown is a black and white print processed from the original color-infrared photograph.

In the Skylab-4 Visual Observations Project, some 300 handheld camera photographs of snowcovered areas were taken by the crew. One such photograph, taken on the same pass over Arizona, is shown in Figure 12 (from the original color photograph). Although the resolution of the handheld camera photographs is generally not as good as that of the S190A and S190B, these photographs taken at various viewing angles have been found to be very useful for research purposes.

Figure 7.   HCMM (Heat Capacity Mapping Mission) visible-channel image viewing
the Sierra Nevada, 31 May 1978.

Figure 8. Aerial mosaic viewing central Arizona,
15 January 1974. The following features are in-
dicated: Mormon Lake (A), Ashurst Rim (B), power-
transmission line swath (C), and Stoneman Lake (D).

16
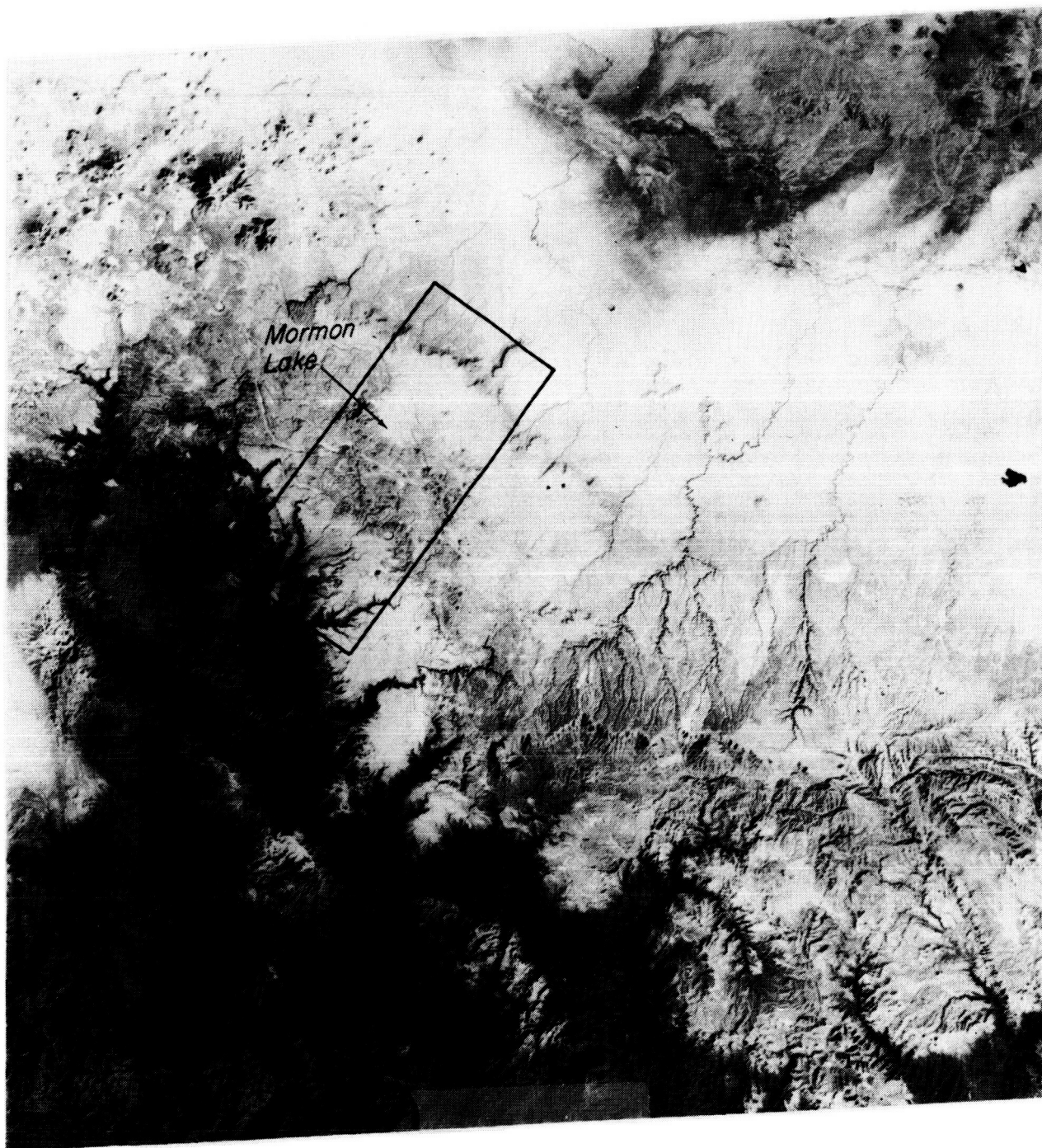
Figure 9.   Landsat-1 MSS-6 image covering central Arizona, 27 January 1974. The area shown in the aerial photograph (Figure 8) is outlined.

Figure 10. Skylab-4 S190A camera station 6 (0.5 - 0.6 μm) photograph viewing central Arizona, 14 January 1974. The area shown in the aerial photograph (Figure 8) is outlined.

18
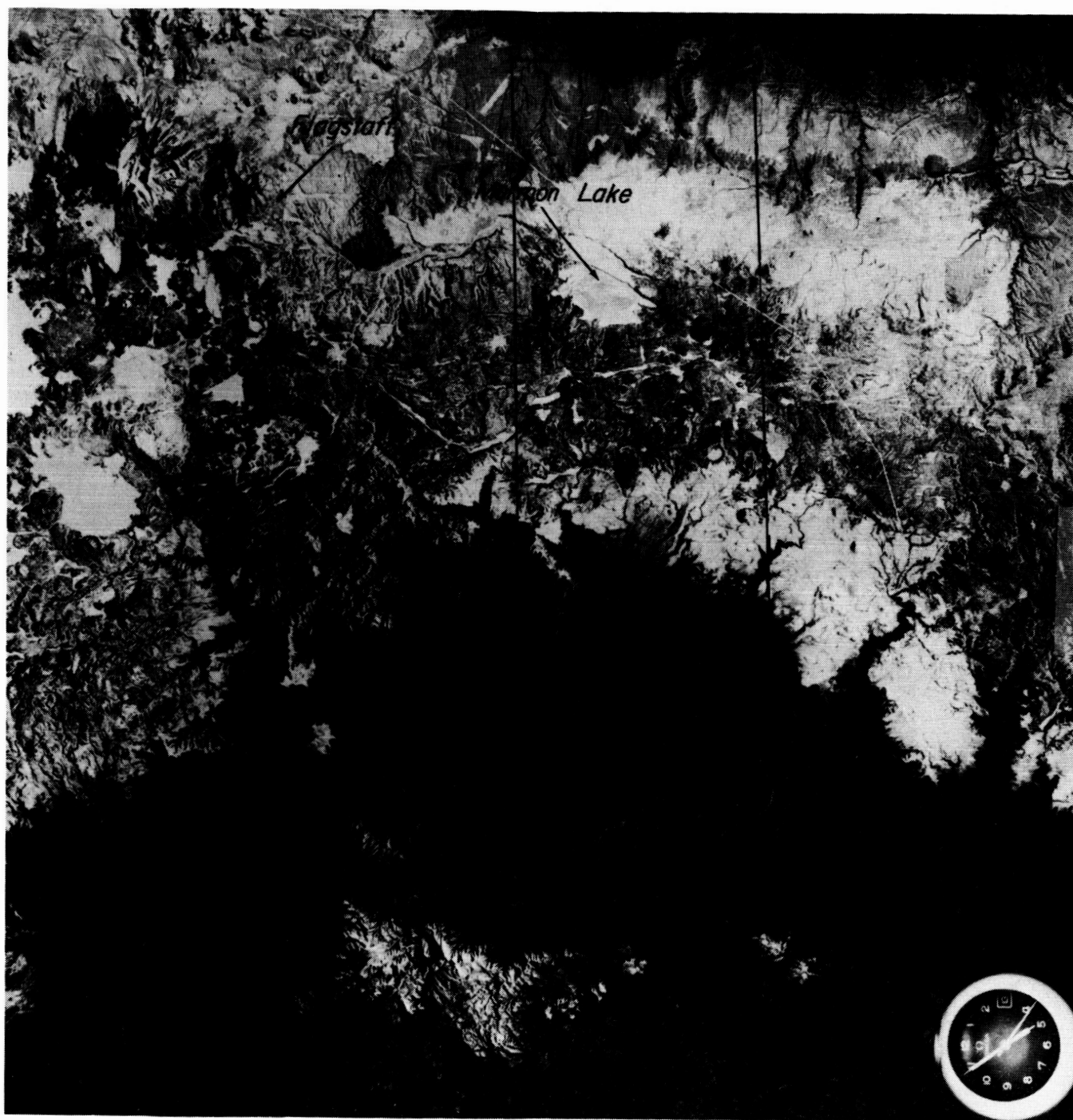
Figure 11. Skylab-4 S190B black and white of aerial color photograph (0.4 –
            0.7 μm) viewing central Arizona on 14 January 1974. The area
            shown in the aerial photograph (Figure 8) is outlined.
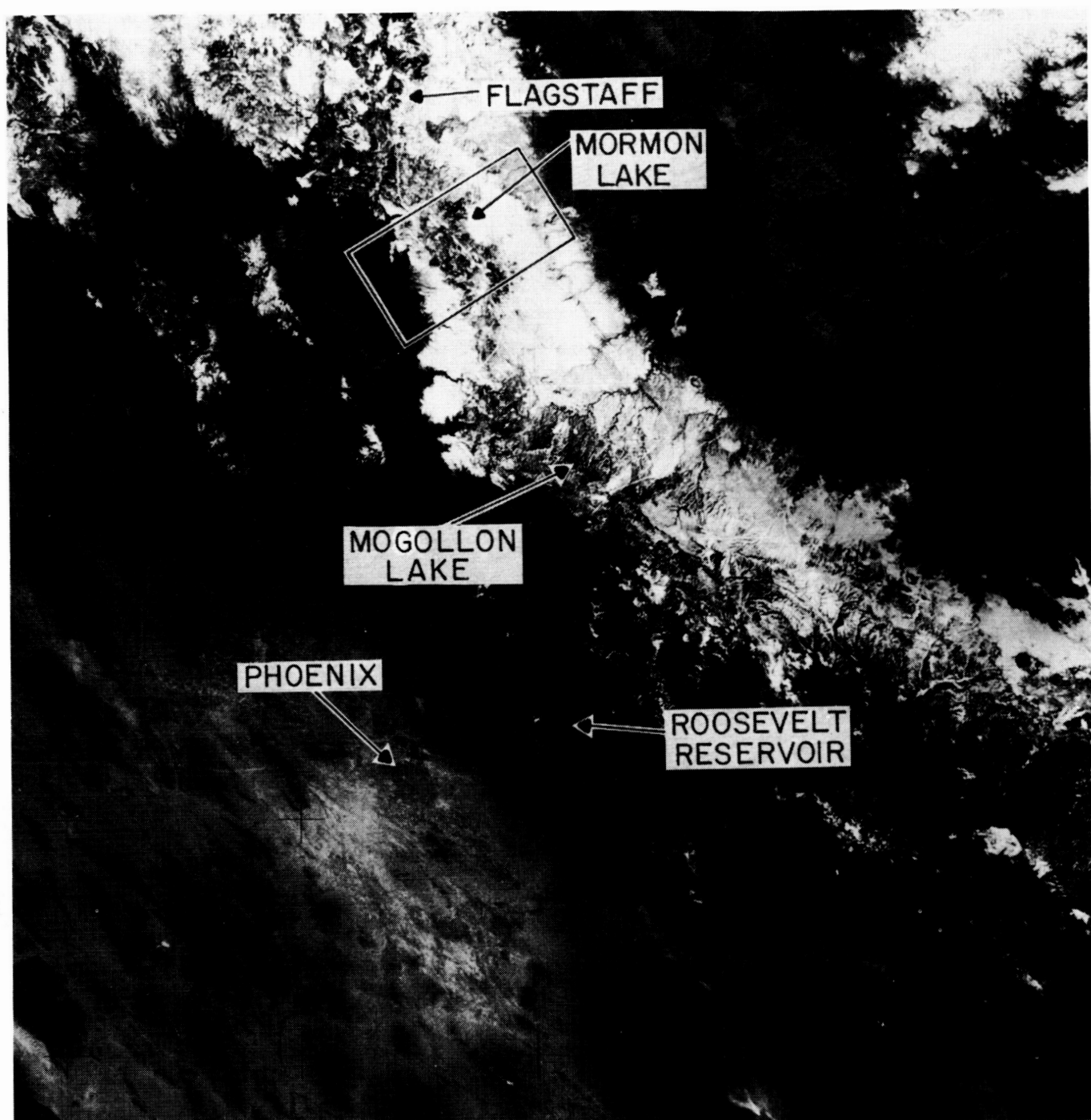
Figure 12. Skylab-4 hand-held camera photograph (from original color photograph) viewing central Arizona on 14 January 1974. The area shown in the aerial photograph (Figure 8) is outlined.

Although it was a much shorter mission (during July 1975) and not designed primarily for scientific data collection, the Apollo-Soyuz Test Project (ASTP) also provided some photographs over snowcovered mountains in the Pacific Northwest and Canada. The photographs are similar to those taken by the Skylab crew. The application to snow mapping of data from manned space flights is discussed more thoroughly in references listed in an earlier section.

DESCRIPTION OF THE FOUR ASVT STUDY AREAS

The four ASVT study areas - Arizona, California, Colorado, and the Northwest - provide excellent examples for describing methods to map snowcover from satellites and to incorporate snowcover area into runoff prediction schemes. Each study area has differing characteristics with regard to the type of terrain, forest cover, and climate. Thus, these four areas present a wide-range of characteristics, which can be extrapolated to other geographic locations. The specific watersheds within each area that have been used in the ASVT are described in the following sections.

Arizona

The Salt-Verde watershed, which comprises the Arizona study area and includes about 34,000 square kilometers (13,000 square miles) in central Arizona, and ranges from 400 to 3,900 meters (1,325 to 12,670 feet) above mean sea level, is shown in Figure 13. The overall Arizona study area is covered by the GOES image shown in Figure 5; a portion of the Salt-Verde watershed is also covered by the images shown in Figures 8 through 12.

Three separate drainage basins, the Salt, Verde, and Tonto, comprise the watershed, and runoff from these basins flows into six reservoirs on the Salt and Verde Rivers. These reservoirs are operated by the Salt River Project to provide hydroelectric power, and municipal, industrial, and irrigation water to more than one million people and 250,000 acres of land. They have a combined storage capacity of approximately 2.5 cubic kilometers (two million acre-feet).

The Salt-Verde watershed is indicated on land usage charts to consist of "forest and woodland, grazed" or "open woodland, grazed", with the predominant growth in the forested areas being Ponderosa Pine. The growth in other areas consists of Juniper zones and grasslands.

The Arizona snowpack is extremely variable from year to year because of its location at the southern edge of the continental snowpack, and rapid snowmelt can occur at lower elevation areas at anytime during the snow season. The annual precipitation amount generally ranges from 250 to 650 millimeters (10 to 25 inches).

California

The California ASVT was divided into two areas to test better the range of conditions found in California. The northern study area originally covered 24 watersheds and sub-watersheds in or adjacent to the Sacramento River above Shasta Dam and the Feather River above Oroville Dam. The southern study area was originally defined as 14 watersheds and sub-watersheds in or adjacent to
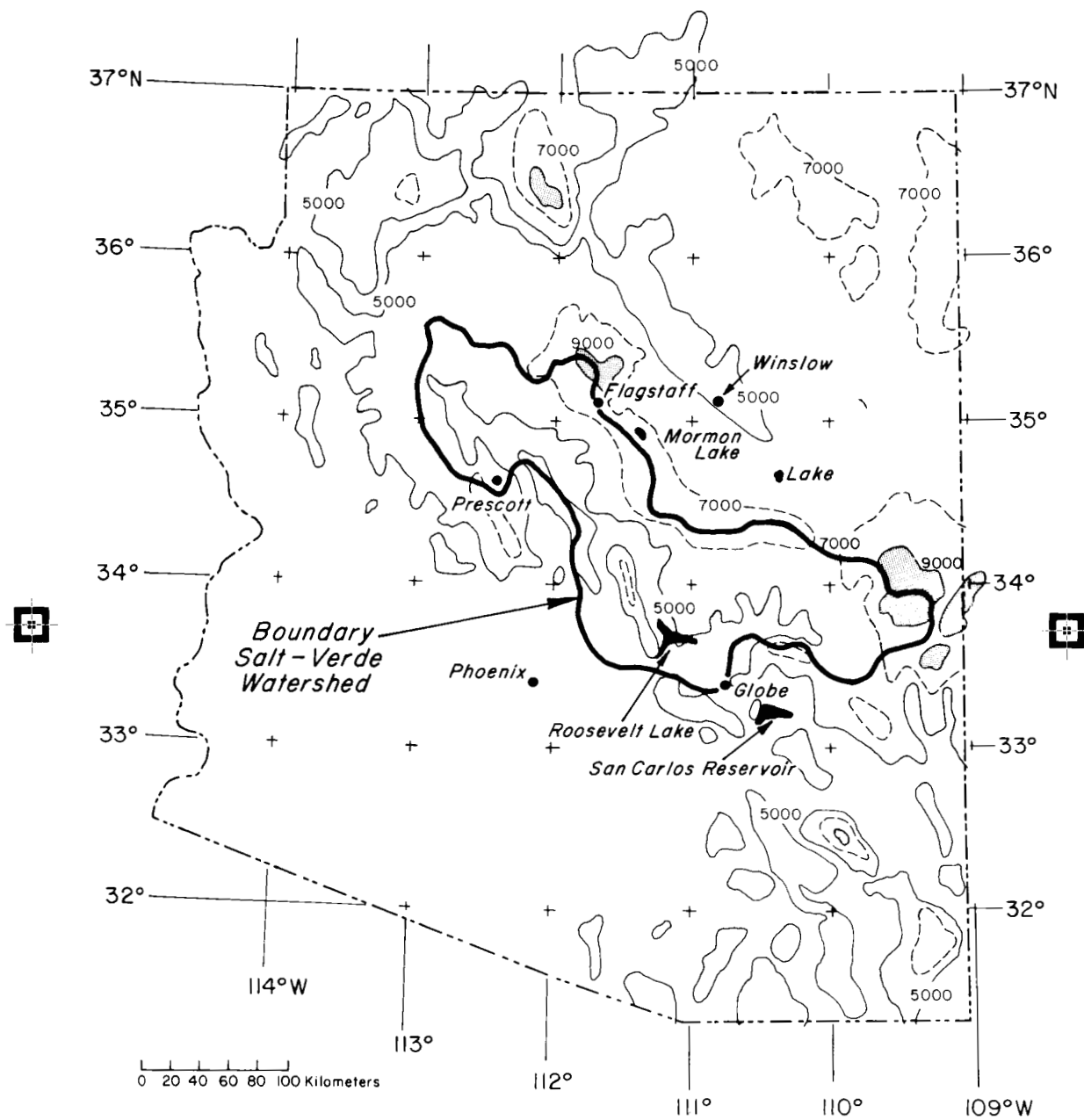
Figure 13. Map showing Salt-Verde Watershed, Arizona ASVT test site. Contours for 1500 m (5000 ft), 2100 m (7000 ft) and 2700 m (9000 ft) are indicated.

the San Joaquin, Kings, Kaweah, Tule and Kern River Basins. However, from a practical standpoint, it was decided that beginning with the 1977-78 water year, approximately 20 major basins throughout the state would be interpreted for snowcovered area periodically during the period of accumulation and more continuously during the period of melt or depletion, eliminating much of the detailed work which was required in analysis of the smaller basins. The location of these study areas is shown in Figure 14. Satellite images covering all or a portion of the California study area are shown in Figures 1, 2, 3 and 5.

The southern area represents the high elevations of the Sierra Nevada where snowcover is relatively stable, and where up to 75 percent of the annual runoff occurs during the April to July snowmelt period. Approximately three-fourths of the San Joaquin Basin is above 2,000 meters (6,500 feet) in elevation, while about half of the Kings Basin is above 2,500 meters (8,200 feet). The altitude of the Kern Basin ranges from about 750 meters (2,460 feet) to more than 4,000 meters (13,120 feet); Mt. Whitney, the highest point (4,418 meters [14,495 feet]) in the 48 contiguous states is in the Kern Basin. The Kaweah and Tule Basins are both lower in elevation, with the entire Tule Basin lying below 2,250 meters (7,380 feet).

The precipitation characteristics of the southern area are described by Rango et al (Reference 22). The average annual precipitation at the 2,750 meter (9,000 foot) elevation in the Kings River Basin is about 890 millimeters (35 inches). Precipitation measurements made along the frontal slope at the western side of the basin appear to be representative of, or at least proportional to, precipitation at the higher elevations, although some minor variations may occur. In the Kern River Basin, precipitation varies considerably with elevation and location within the basin. At 2,750 meters (9,000 feet), average annual precipitation along the Great Western Divide exceeds 890 millimeters (35 inches), while at the same elevation along the Sierra crest, precipitation may be as low as 410 millimeters (16 inches). Precipitation, snowpack accumulation, and snowcover appear much more variable over the Kern Basin than over the Kings Basin.

The northern area is characterized by lower elevations and more transient areas of snowcover; in this area, 45 percent of the annual runoff occurs during the April to July snowmelt period. The sub-basins vary in size from 100 square kilometers (38 square miles) to 16,000 square kilometers (6,400 square miles). Use of the sub-basins allows cross-checks between adjacent and nearby basins when cloud cover, missing imagery, or other factors contribute to loss of data from a specific basin or portion of the study area on any given day. Average annual precipitation amount in the northern study area (the combined Sacramento and Feather Basins) is about 990 millimeters (39 inches).

Land use charts depict the Sierras as consisting primarily of "forest and woodland, mostly ungrazed", with some "forest and woodland, grazed". In a slightly different classification scheme, Anderson (Reference 30) designates the higher elevation as "Alpine" and "Commercial Forest". In this scheme, a narrow band of "lower Conifer Zone" borders the commercial forest zone along the western slope of the Sierras, with the lower elevation designated as "Woodland-Brush-Grass Zone". Despite the apparent abundance of forest-covered land, Court (Reference 31) points out that in total area, the Kings River Basin
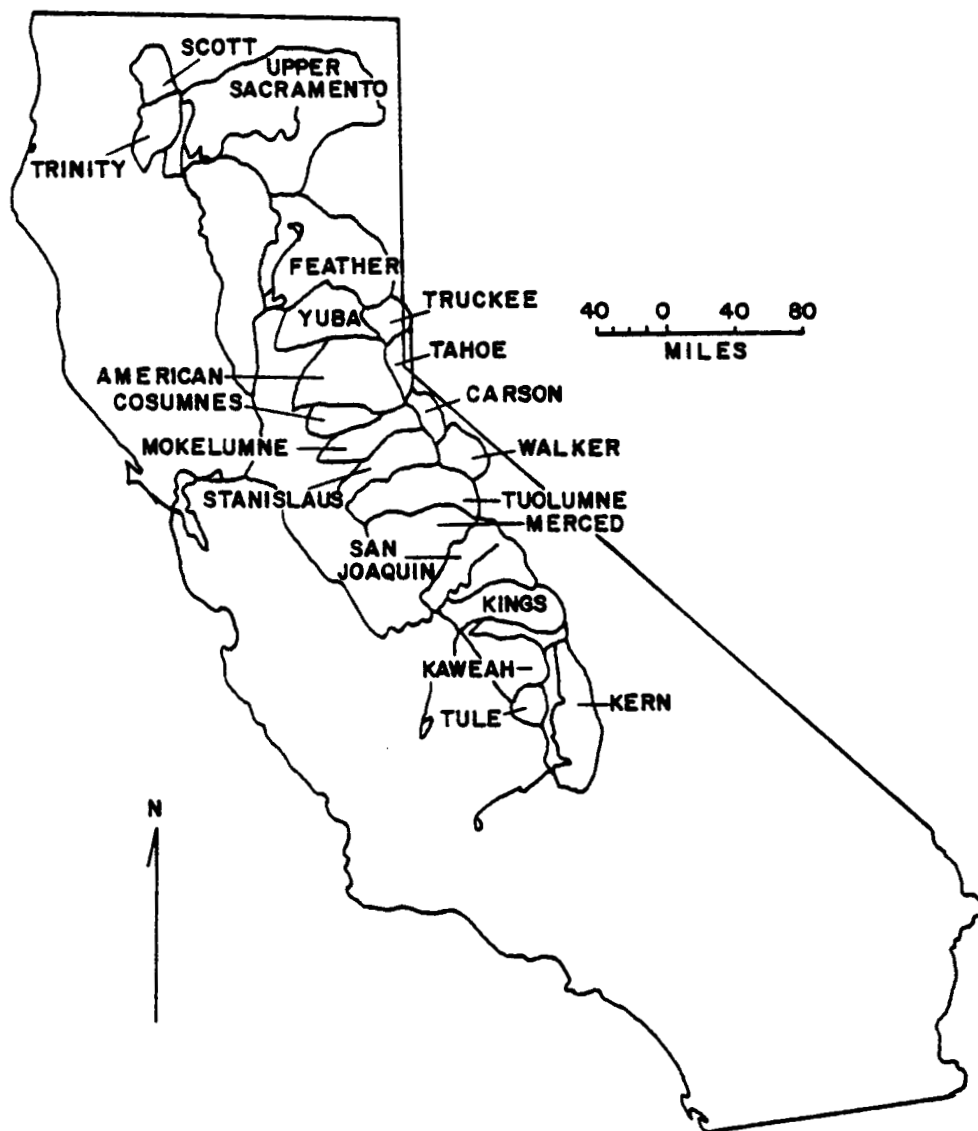
Figure 14. Map showing location of California ASVT study basins.

is only 28% forested; furthermore, trees are so sparse in the forested area
that only about 17% of the basin is covered by the tree canopy. For the
Sierras as a whole, Court reports that 76% of the area is exposed to the sky.

Colorado

The Rio Grande Basin in Colorado was chosen as the primary drainage for study
and the Upper Arkansas River as a secondary study basin. Within the Rio Grande
Basin, five watersheds were selected for detailed analysis. In all, six water-
sheds encompassing some 9,335 km^2 (3,604 mi^2) were analyzed in the study,
which corresponded to streamflow gaging stations currently forecasted by the
Soil Conservation Service. They include the Arkansas River near Wellsville,
Rio Grande above Del Norte, South Fork Rio Grande at South Fork, Alamosa
River above Terrace Reservoir, Conejos River near Mogote, and Culebra Creek at
San Luis (Figure 15). The latter five watersheds are all in the Rio Grande
Basin and flow into the San Luis Valley where they comprise the mainstem of
the Rio Grande.

Both the Rio Grande and Arkansas basins represent river systems whose primary
source of water is snowmelt. The San Luis Valley is a virtual desert which
could produce little in terms of agriculture were it not for the snowfed
streams which enter it. Mean annual precipitation on the valley floor, which
averages 2,460 meters (7,500 feet) elevation, is only 178 millimeters (7
inches), whereas at the headwaters at elevations to 4,267 meters (14,000 feet)
it averages 1,143 millimeters (45 inches) annually. Over 80 percent of the
annual flow of the Rio Grande is attributable to the snowpack contribution
which runs off in the April through September period.

The mountain snowpack normally begins building in late October and reaches a
maximum near the first of April. In early April, melt at lower elevations is
occurring while at the higher elevations accumulation may continue into the
first part of May. The net effect is generally a decline in the overall snow-
pack commencing near the first of April. However, frequent large storms during
April and early May can have a significant impact on the basin's total water
production.

Permanent snowpacks in this region are characteristically cold and of lighter
density than those found in areas affected by more maritime air masses.
Internal snowpack temperatures are sub-freezing until isothermal conditions
occur late in April and early May. The light density snow is a consequence of
the great distance inland and the relatively high elevations of the mountain
ranges. Snowfall tends to be frequent throughout the winter resulting in a
gradual building of the snowpack as opposed to packs which result from only a
few major storms. The major sources of winter moisture for the area are
Pacific air masses on southwesterly and northwesterly trajectories. Of the
two, southwesterly flow generally provides the most intense storms.

The Arkansas Basin is similar to the Rio Grande. Valley floor elevations are
between 2,438 meters (8,600 feet) and 2,743 meters (9,000 feet) and rise to
heights of 4,389 m (14,400 feet). Mean annual precipitation varies between
250 millimeters (10 inches) on the valley floor to 1016 millimeters (40 inches)
in the highest elevations of the basin. The mountain snowpack produces about
75 percent of the annual flow.

25
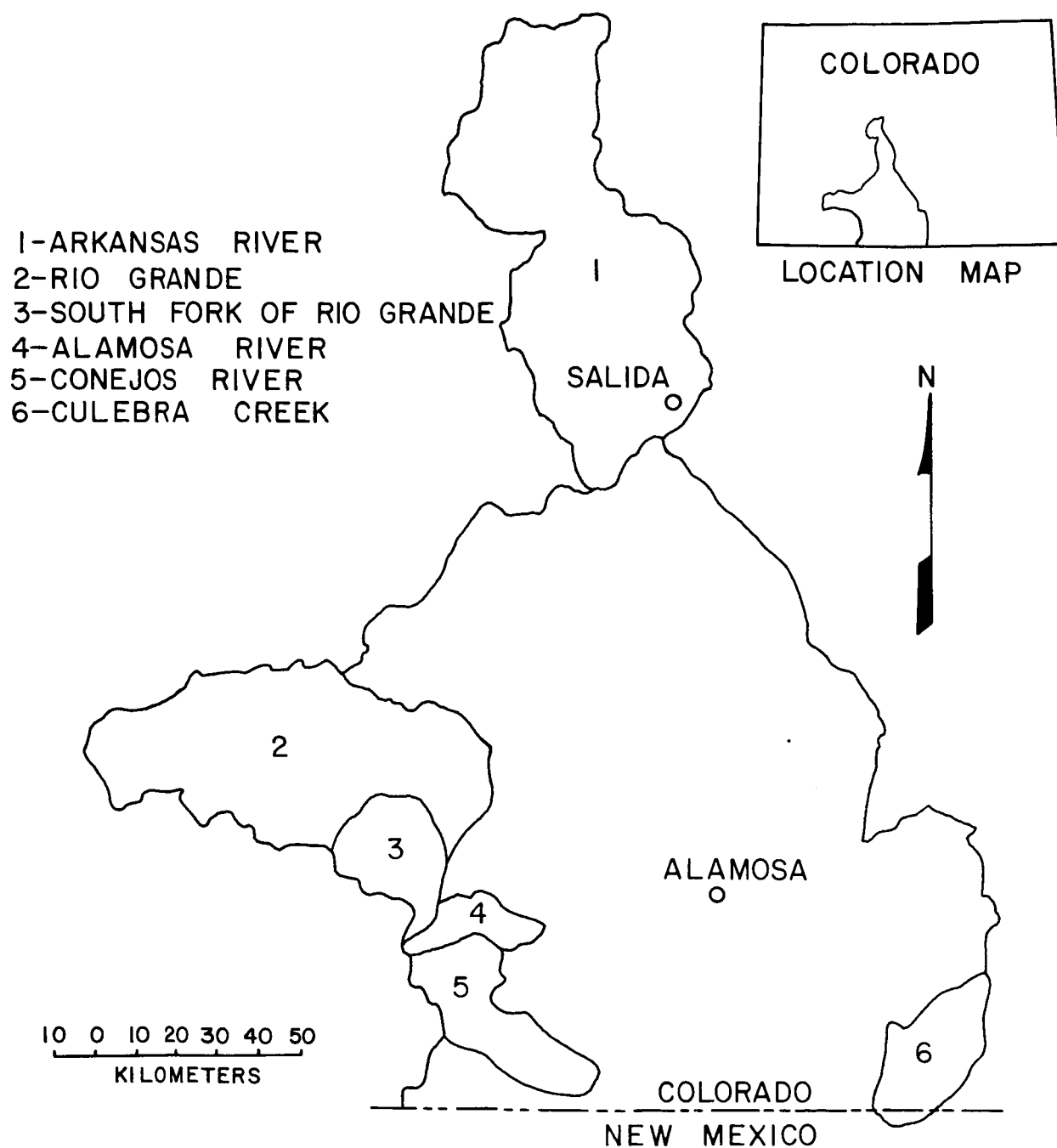
Figure 15. Map showing location of Colorado ASVT study drainages.

26

Figure 16 is a photomosaic of the study area produced from Landsat imagery taken in August 1978. It has been reduced to 66 percent of its original scale of 1:1,000,000, yet it provides an excellent means of relating the basins in their geographic and topographic setting.

The major initial effort in the Colorado ASVT was concentrated on the Conejos River Drainage. This is a small drainage of fairly high elevation with an average of 1.5 meters (5 feet) of snow at medium elevations. This drainage produces an average of 246.6 hectometers^3 (200,000 acre-feet) of water annually.

The Conejos Basin contains mostly uplands with the river splitting the basin. Much of the drainage is 3,048 meters (10,000 feet) or more above sea level. Waters from the river provide irrigation for acreage in the San Luis Valley in Colorado and areas along its course in New Mexico. Without irrigation water, the valley is of little commercial value. It is covered by low sage and rabbitbrush. Where water is available, high value truck crops such as lettuce, onions, and potatoes are grown. Two Landsat images of the Conejos Basin, before and immediately following a major spring snowfall, are shown in Figures 17 and 18.

Northwest

The Columbia River Basin has an area of more than 668,200 km^2 (258,000 mi^2), almost twice the size of California. The Basin contains most of Washington, Oregon, and Idaho; that part of Montana west of the Rockies; small areas of Wyoming, Utah, and Nevada; and the southeastern part of British Columbia.

The Columbia River is second only to the Mississippi in average runoff for rivers in the United States. The average annual precipitation over the Basin is about 71 centimeters (28 inches). Of this amount, about 30.5 centimeters (12 inches) is returned to the atmosphere by evapotranspiration and 2.54 centimeters (1 inch) of the amount withdrawn for beneficial use is consumed, leaving 38 centimeters (15 inches) for runoff.

A total of five sub-basins of the Columbia River Basin were selected for investigation in the ASVT study program. These sub-basins, shown in Figure 19, include the Upper Snake, Boise, Dworshak, Libby, and Hungry Horse.

Basin Description

Upper Snake - Wyoming and Idaho

This basin includes approximately 13,340 km^2 (5,150 mi^2) above Palisades Reservoir. The basin rises from 1,714 meters (5,620 feet) above mean sea level at the reservoir, to 4,199 meters (13,766 feet) on Grand Teton. The mean elevation is 2,410 meters (7,900 feet) and virtually all of the basin lies above 1,830 meters (6,000 feet). The entire basin lies high enough that snow is present year-round on a significant portion of the basin lying above the 2,745 meter (9,000 foot) elevation. As is characteristic of the Northwest study area, the Upper Snake Basin is heavily forested. The average annual precipi-

27
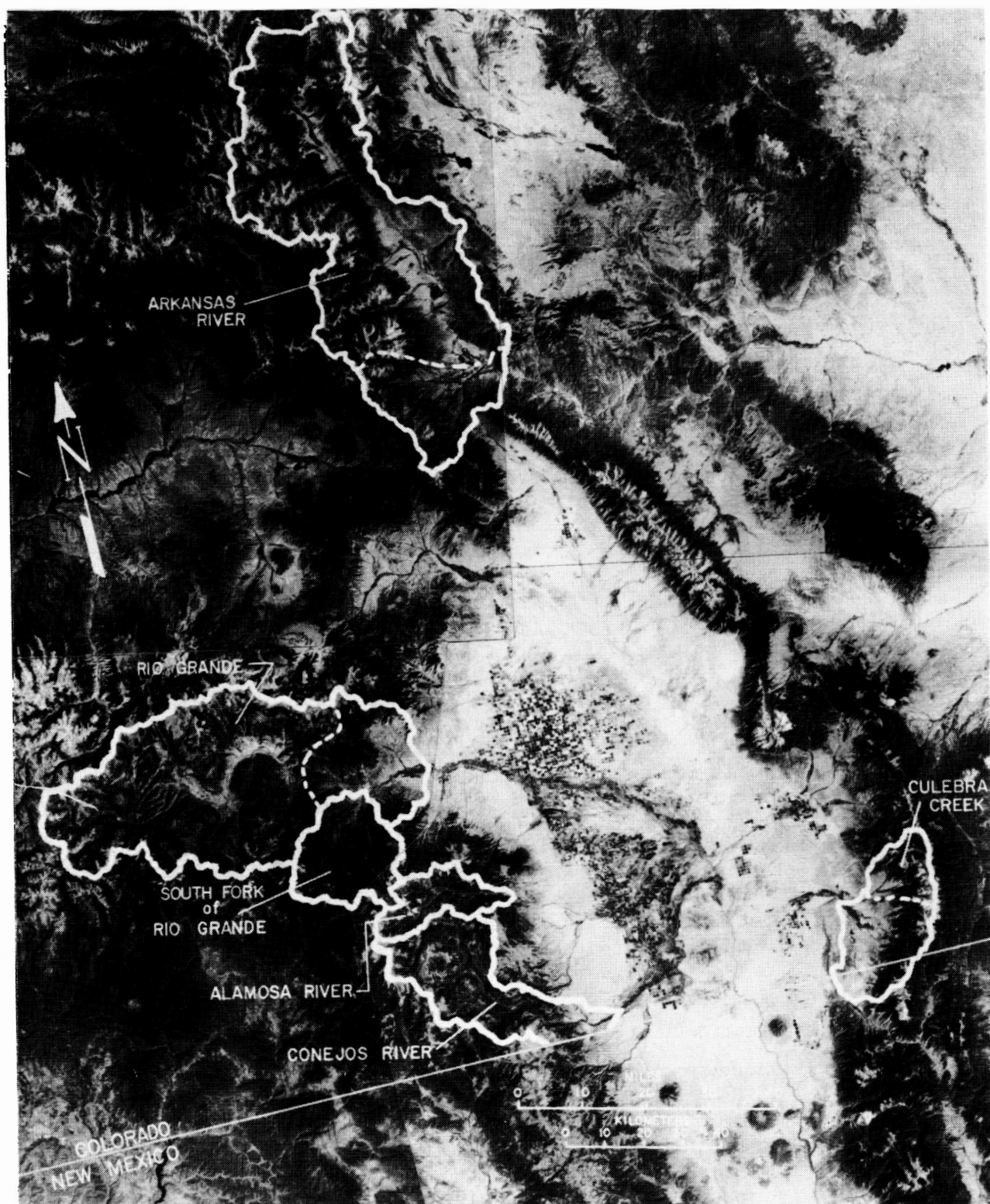
Figure 16. Photomosaic of Colorado ASVT study drainages produced from Landsat imagery of August 1978.

Figure 17.   Landsat-3 MSS-5 image viewing snowcover on Conejos Basin on 21
April 1978.
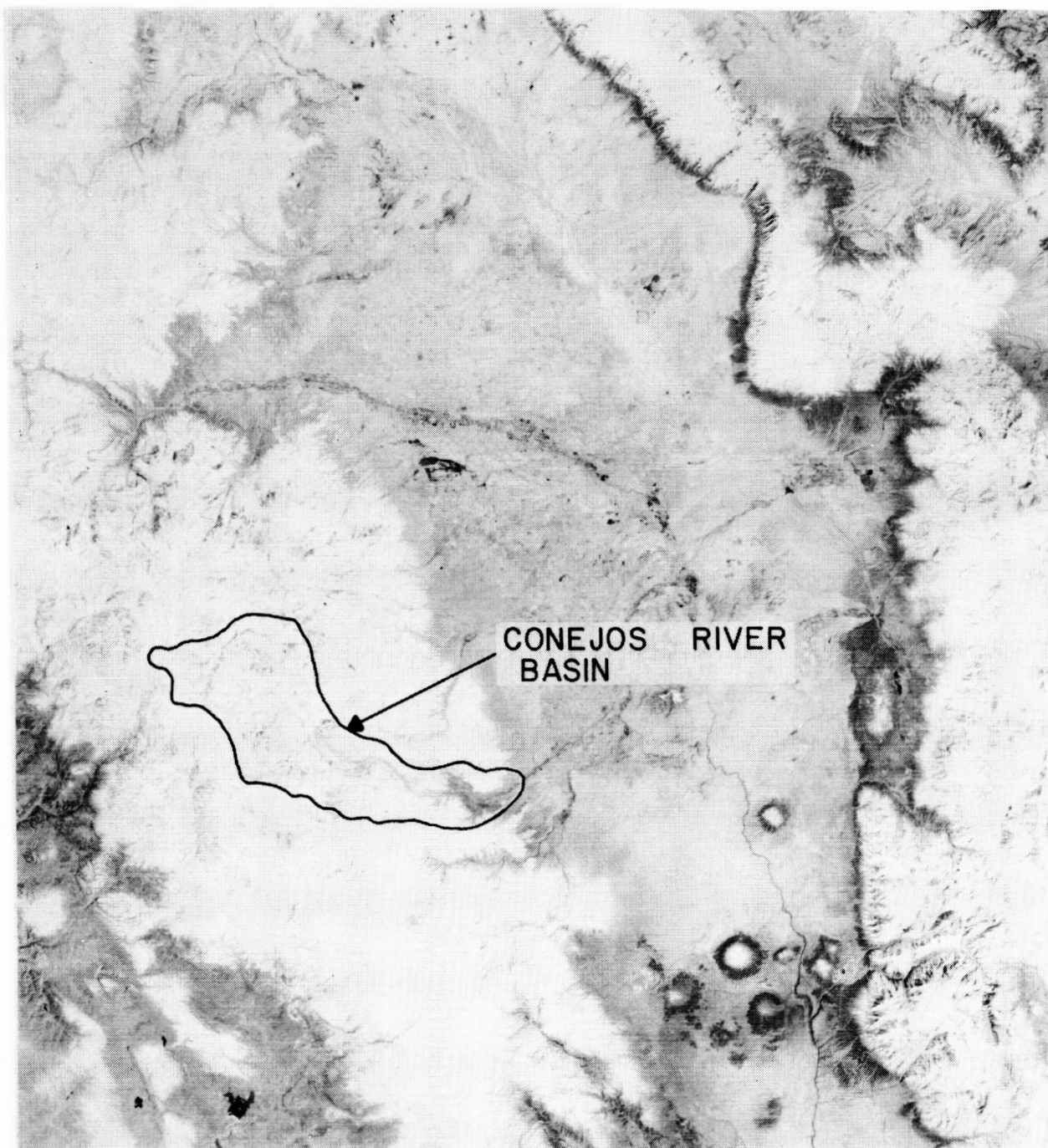
Figure 18.   Landsat-3 MSS-5 image viewing snowcover on Conejos Basin on 9 May
1978.
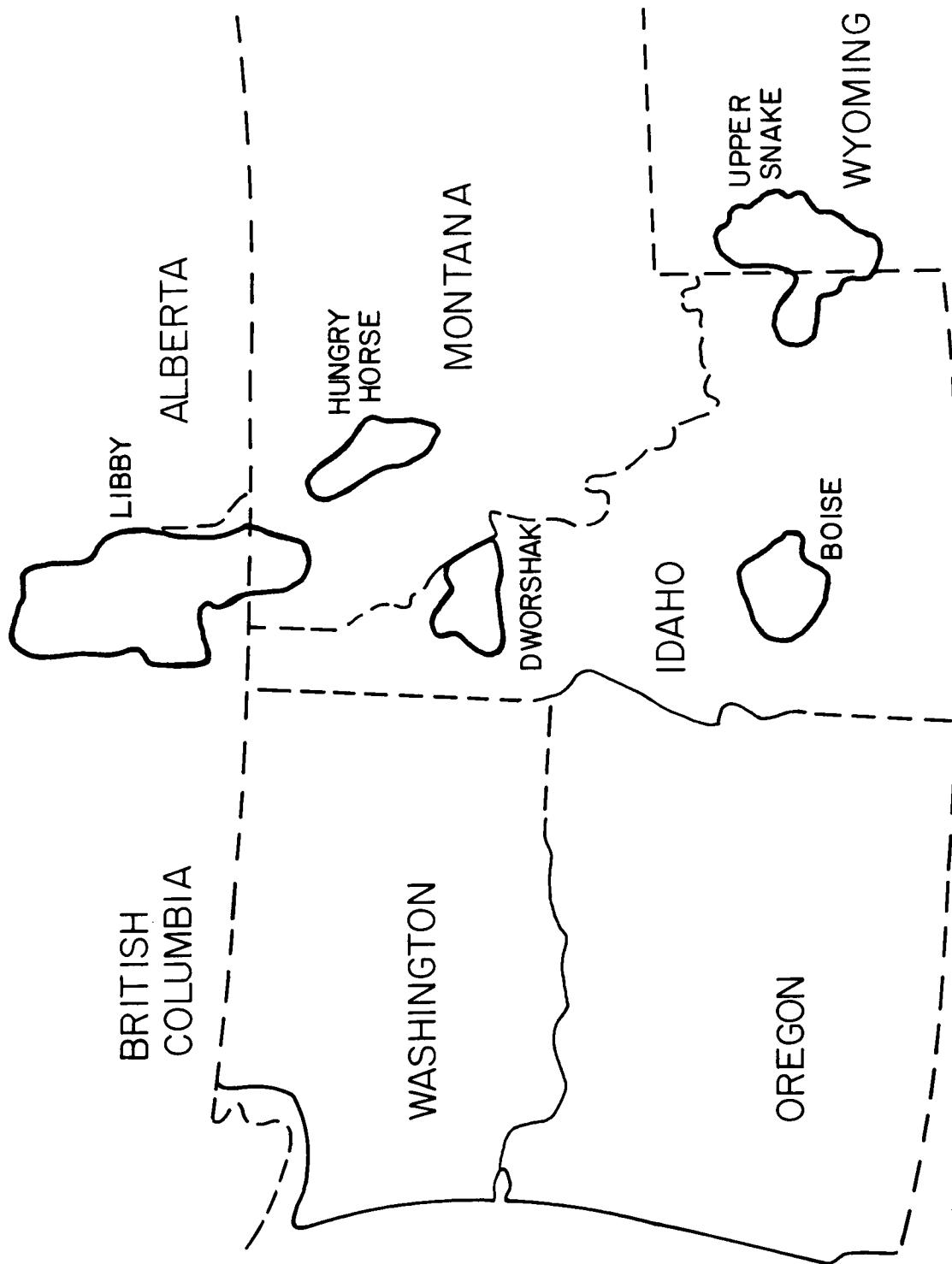
Figure 19. Map showing location of five sub-basins of the Columbia River Basin selected for analyses in the Northwest ASVT study program.

tation amount across this basin is approximately 58 centimeters (23 inches).

Boise - Idaho

The Boise River drains approximately 7,252 km^2 (2,800 mi^2) above Lucky Peak Dam. Basin elevations vary from 3,249 meters (10,651 feet) atop Snowyside Peak to 933 meters (3,060 feet) at the dam's water surface. Virtually all of the basin is above 1,220 meters (4,000 feet) with a mean elevation of 1,891 meters (6,200 feet). The entire basin is sufficiently high that large areas of snow are deposited and stay through the winter and spring. In the upper ridges surrounding the basin, there are a few permanent snowpacks. Tree cover, slope and aspect for this basin are similar to the Upper Snake Basin. The average annual precipitation amount across the Boise Basin is about 60 centimeters (24 inches).

Dworshak - Idaho

The North Fork of the Clearwater River drains an area of 6,319 km^2 (2,440 mi^2) above Dworshak Dam. Elevations range from 488 meters (1,600 feet) at the dam's water surface, to 2,450 meters (8,036 feet) atop Democrat Mountain. The basin has an average elevation of about 1,220 meters (4,000 feet), and is a topographically rugged, densely timbered, largely undeveloped area. The Dworshak Basin is heavily forested and has particularly steep terrain. Annual average precipitation across this basin is approximately 101 centimeters (40 inches).

Libby - Montana and British Columbia

The Kootenai River drains an area 23,271 km^2 (8,985 mi^2) in the United States and Canada above Libby Dam in Montana. This basin rises from 750 meters (2,459 feet) above mean sea level at the dam's surface, to 3,620 meters (11,870 feet) at the summit of Mount Assiniboine in British Columbia. The mean elevation of the basin is about 1,982 meters (6,500 feet), and numerous mountain peaks are above 2,440 meters (8,000 feet), with six peaks exceeding 3,050 meters (10,000 feet). The Libby Basin has a dense tree canopy and steeply sloping terrain; also, limestone or "white" rock outcroppings above the timberline are highly reflective. The average annual precipitation amount for this basin is about 63 centimeters (25 inches).

Hungry Horse - Montana

The South Fork of the Flathead River drains an area of 4,284 km^2 (1,654 mi^2) above Hungry Horse Dam. Elevations in the basin range from 1,086 meters (3,560 feet) at the dam's water surface, to 2,754 meters (9,356 feet) atop Holland Peak. The basin has an average elevation of approximately 1,830 meters (6,000 feet). Tree cover in the basin varies from clearcut areas near the reservoir to medium dense evergreen stands in the headwaters; the terrain is rugged with steep slopes. Average annual precipitation across this basin is about 101 centimeters (40 inches). Two Landsat images of the Hungry Horse Basin are discussed in the following section.

METHODS FOR IDENTIFYING AND MAPPING SNOWCOVER IN SATELLITE DATA

Photointerpretation Techniques Using Satellite Imagery

Snowcover is one of the most readily identifiable of all earth resources from satellite imagery. In this section, techniques for identifying and mapping snowcover from Landsat and VHRR imagery are discussed; although GOES imagery is not discussed specifically, the techniques for analyzing VHRR imagery apply in general to GOES, as well. In addition, the methods for presenting snow-covered area, comparisons with aerial survey, machine processing techniques, and snow mapping problems and solutions are also reviewed.

Identifying Snowcover in Satellite Imagery

Through careful analysis of satellite images, snow can be identified and the boundaries of snowcovered areas accurately located. However, a certain amount of subjective interpretation may be necessary when dealing with forest and shadow problems. In nonforested terrain, all areas with a continuous bright-ness distinctly greater than the normal dark background, that are identified as being essentially cloud-free, should be mapped as being snowcovered. The snowline enclosing all such areas represents the limit of a snow accumulation of approximately 2.5 centimeters (1 inch) or more. Areas that appear "mottled" (alternating dark and grey) usually are indicative of less than 2.5 centi-meters of snow.

In mountainous terrain, the snowline is mapped at the edge of the brighter tone without regard to brightness variations resulting from forest effects or mountain shadows within the overall area deduced to be snowcovered. The snow-line may at times be obscured because of dense forest cover (see following section for further discussion of forest effects). Because of the deeper snowpacks and steep terrain, the visible snowline in a mountainous area may represent a snow depth of considerably more than 2.5 centimeters. An example of the placement of the snowline on a Landsat image of the southern Sierras is shown in Figure 20.

In the NOAA VHRR visible channel and also in the two Landsat spectral bands that are in the visible range, snow can be readily identified because of its high reflectance in comparison to areas with little or no snowcover. Examina-tion of Landsat images containing snowcover reveals that the contrast between snowcovered and snow-free terrain is greatest in the MSS-5 (0.6 to 0.7 μm) spectral band. Although snow is readily identified in the MSS-4 (0.5 to 0.6 μm) band, the contrast between snow and ground is somewhat less than in the MSS-5 data. Moreover, at higher sun angles snowcovered areas are near satura-tion in the MSS-4 band, causing a loss of some detail in the snow patterns.

Although snow can be detected in longer wavelength bands, the contrast between snowcovered and snow-free terrain is considerably lower than in the visible band.
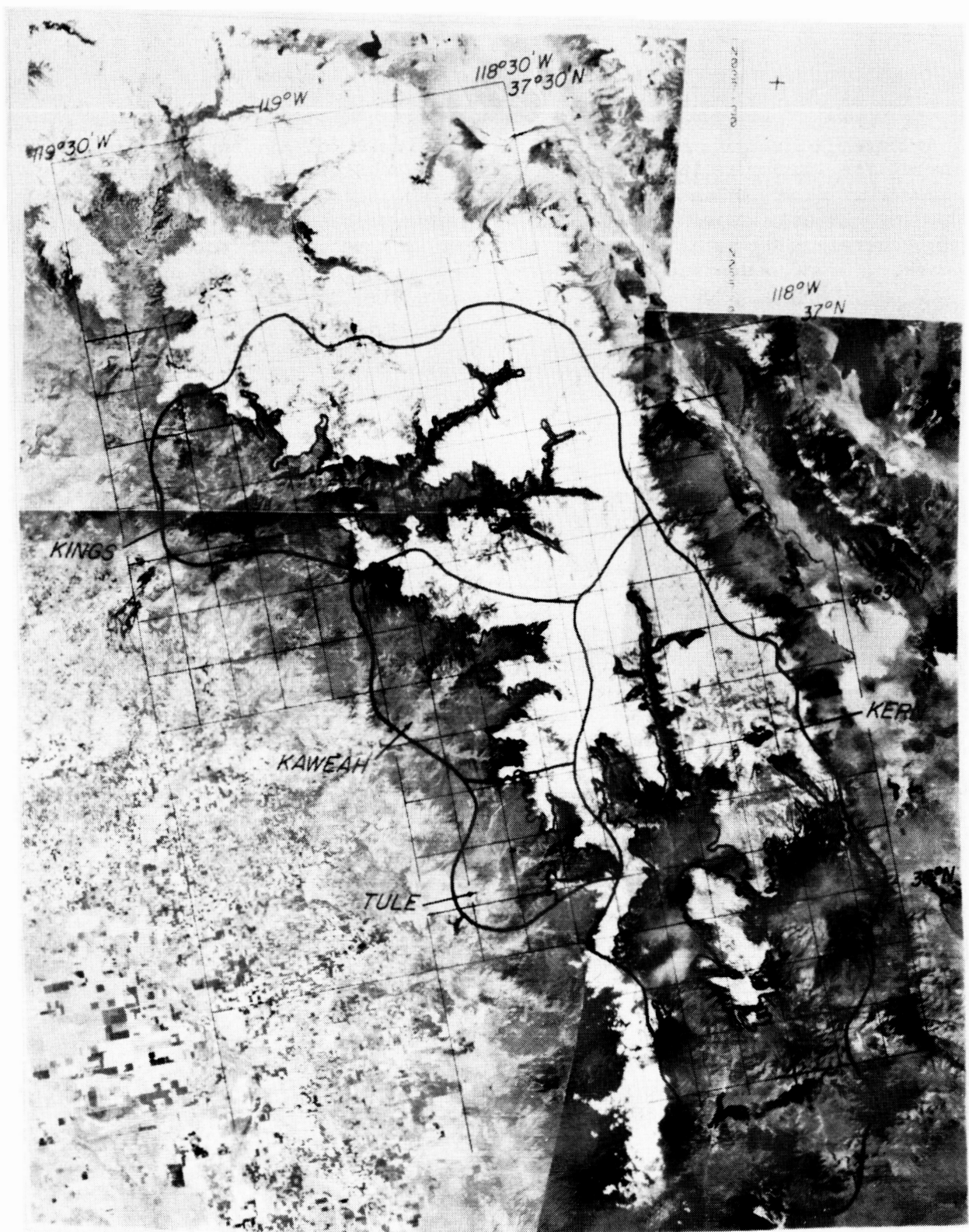
Figure 20. Landsat mosaic of 7 and 8 May 1973 with an outline of individual river basins, a fine mesh grid and snowline extent indicated.

Factors Influencing Snow Mapping Accuracy

Clouds

In the NOAA VHRR and the Landsat visible bands, snowcover and clouds both have
high reflectances. Differentiating between the two is one of the problems in
the use of satellite observations for snowcover analysis. Snowcover can be
distinguished from clouds, however, through the interpretive keys described
below. The differences in the appearance of snow and clouds can be seen in
several of the example images, such as Figures 2, 3 and 6.

- recognition of terrestrial features – because of the im-
  proved resolution of the VHRR imagery and the high resolu-
  tion of the Landsat data, numerous terrestrial features
  can be easily recognized. In addition to natural features
  such as coastlines, lakes, rivers, and boundaries between
  forested and non-forested areas, such man-made features as
  roads, power line swaths, timber cuts, urban areas, and cul-
  tivated fields are detectable in the Landsat imagery. In
  flat terrain areas, such as the mid-west, recognition of
  terrestrial features is the most reliable method to dis-
  tinguish snow from clouds;

- pattern recognition – mountain snowpacks cover the higher
  elevation terrain and, thus, are directly related to the
  geologic structure. Since the configuration of the geolo-
  gic structure of typical mountain ranges is quite differ-
  ent from the patterns of clouds as viewed from space, the
  snowcover can be instantly recognized. In addition,
  within areas of steep terrain, such as the eastern slope
  of the Sierras, the snowline is generally well-defined and
  forms a sharper boundary than is characteristic of most
  cloud edges;

- uniformity of reflectance – snowcover in areas that are
  not forested typically has a more uniform reflectance than
  do clouds. Furthermore, the distinct changes in reflec-
  tance that are associated with forested and non-forested
  areas are not found in cloud patterns. Although clouds
  and snow can have nearly the same reflectivities, snow-
  covered areas are usually smooth textured while clouds are
  often rough or lumpy in appearance;

- cloud shadows – the low sun angle during the winter season
  enhances cloud shadows, and occasionally the shadows of
  narrow cloud bands are observed on an underlying snow sur-
  face. Most common, however, is the detection of cloud
  shadows during the spring season when cumuliform clouds
  tend to develop over mountain ranges. Also, at times of
  low sun angle, north slopes of mountain ridges may also be
  in shadow; these shadows, however, can be distinguished
  from cloud shadows because they fit the configuration of
  the geological structure; and

- **pattern stability** – since clouds seldom retain the same
  shape for more than a few hours, stable patterns of high
  reflectivity viewed by satellite are indicative of snow-
  cover. Naturally to employ this technique, observations
  a day or more apart are required. When the observations
  are several days apart, the possible changes in snow
  extent, due to either melting or additional snowfall
  associated with a storm passage, must be taken into con-
  sideration.

Forest Cover

Forested areas comprised of dense coniferous growth remain distinctly darker
than areas of deciduous forest, sparse vegetation, or non-forested terrain.
Such areas usually remain dark even with substantial snowcover; as dry snow
tends to filter through and not remain fast to the conifers. Small lakes,
timber cuts, or open land within these areas do, however, appear highly reflec-
tive indicating the existence of snowcover. On occasion, a heavy wet snow will
cling to the tree canopy for a short period causing no difficulty in determin-
ing the existence of snowcover.

Analysis of satellite imagery with regard to detecting snow in forested areas
requires a considerable amount of subjective interpretation. The analyst must
be thoroughly familiar with the area being analyzed. Information on the dis-
tribution of forest can be obtained through reference to land use charts,
topographic maps, and other sources. Additionally, it is extremely helpful to
know what the forest patterns look like in imagery at a time of no snowcover;
Landsat color-composite data, in which vegetated areas are accentuated in
bright red tones, is very helpful for this purpose. Being familiar with the
area in question, the analyst can then make a judgment on the snow extent by
examining the overall grey-tone (all areas, except those with dense conifer
growth, do exhibit some change in grey-tone with snowcover), checking the grey-
tone of the open areas within overall forested terrain, and identifying snow-
cover in non-forested land at lower elevations.

Two Landsat images of the Hungry Horse Basin in the Northwest study area,
shown in Figures 21 and 22, illustrate the effects of forest cover on identi-
fication of snow. On 7 March (Figure 21), the basin was mapped as being 95
percent snowcovered, despite the amount of darker-toned area; the bright,
clear-cut areas are an indication that the heavily forested terrain is snow-
covered. On 18 May (Figure 22), the snowcovered area within the Hungry Horse
Basin was mapped as 48 percent; by this date, the clear-cut areas are snow-
free and appear dark.

Some simple image enhancement techniques involving the over-exposure of film
to increase the reflectance of the snowpack in forested areas can also be used
for improving the location of the snowline. The snowcover in forested areas,
when observed from Landsat, takes on a mottled grey appearance resulting from
a certain amount of highly reflective snow showing through the tree canopy.
By increasing the exposure time for producing diazo prints, the reflectance of
the mottled grey area (forest with snow) can be increased to a level approxi-
mately equal to adjacent open snow areas. The contrast between forest with

36

Figure 21. Landsat MSS-5 image viewing snowcover extent on Hungry
Horse Basin, 7 March 1976. The basin is 95 percent snowcovered on
this date.

Figure 22. Landsat MSS-5 image viewing snowcover extent on Hungry Horse Basin, 18 May 1976. The basin is 48 percent snowcovered on this date.

and without snow is greatly enhanced and the positioning of the snowline in the forest is markedly facilitated (Reference 32). This method is not as effective in regions with extremely dense forest cover, such as the Northwest, where the tree canopy may completely obscure the underlying snowpack.

Bare Rock

In the late spring and early summer, partial snowcover may be difficult to distinguish from highly reflecting bare rock. In using Landsat imagery, for example, data from the late summer when no snow is present should be studied to become thoroughly familiar with the terrain and vegetation patterns. Color composite data can also be useful for this purpose.

A Landsat image taken during the 1977 drought in California is shown in Figure 23. The snowcovered area near Lake Tahoe can be contrasted with the more normal amount at about the same date a year later (Figure 1). Close inspection of the 1977 image further indicates that even the terrain that at first appears to be snowcovered, in fact, likely has considerable bare rock (again, a comparison with Figure 1 shows that these areas are more uniformly bright in the heavier snow year). Analysts have found that aerial surveys of suspect areas are very helpful for becoming familiar with the terrain and subsequently being able to distinguish bare rock from snow.

Mountain Shadows

During the mid-winter period, low sun angles produce mountain shadows that can cause ambiguity in locating the snowline. In Landsat and VHRR images, the reflectance of a north-facing ridge that is partially or totally snowcovered may appear the same as the reflectance of terrain that is completely snow-free (see Figure 20). Mountain shadows can be a serious problem in areas such as the Sierra Nevada because of the numerous ridges and canyons in that mountain range. The processing of enlarged prints (scale - 1:500,000) from the Landsat 70 mm negatives, using various exposure times in order to bring out more detail in the dark shadow areas (similar to enhancement for snow in forest), aids considerably in alleviating the mountain shadow problem. In fact, the enlargements will allow detection of snow/no-snow boundaries which are obscured in original size imagery. An example is given in Figure 24, where an original Landsat image viewing the southern Sierras on 2 January 1973 is shown in Figure 24a, and the reprocessed enlargement in Figure 24b.

If the analyst does not have access to the original negative or to the photographic equipment needed to reprocess the negative, the snowline can be located in shadowed terrain through subjective interpretation. In mid-winter, the snowcover often extends to lower elevations than where the shadows are (see Figures 20 and 24). By noting where the snowline is located on a non-shadowed area, it is possible to make a judgment as to whether a dark pattern is an area of no-snow or a snowcovered area in shadow. Later in the winter and spring the snow distribution may be even less, and the analyst must account for there probably being more snow on the north-facing than on the south-facing slopes. Fortunately, because of higher sun angles, the shadow problem is not as severe in the spring.
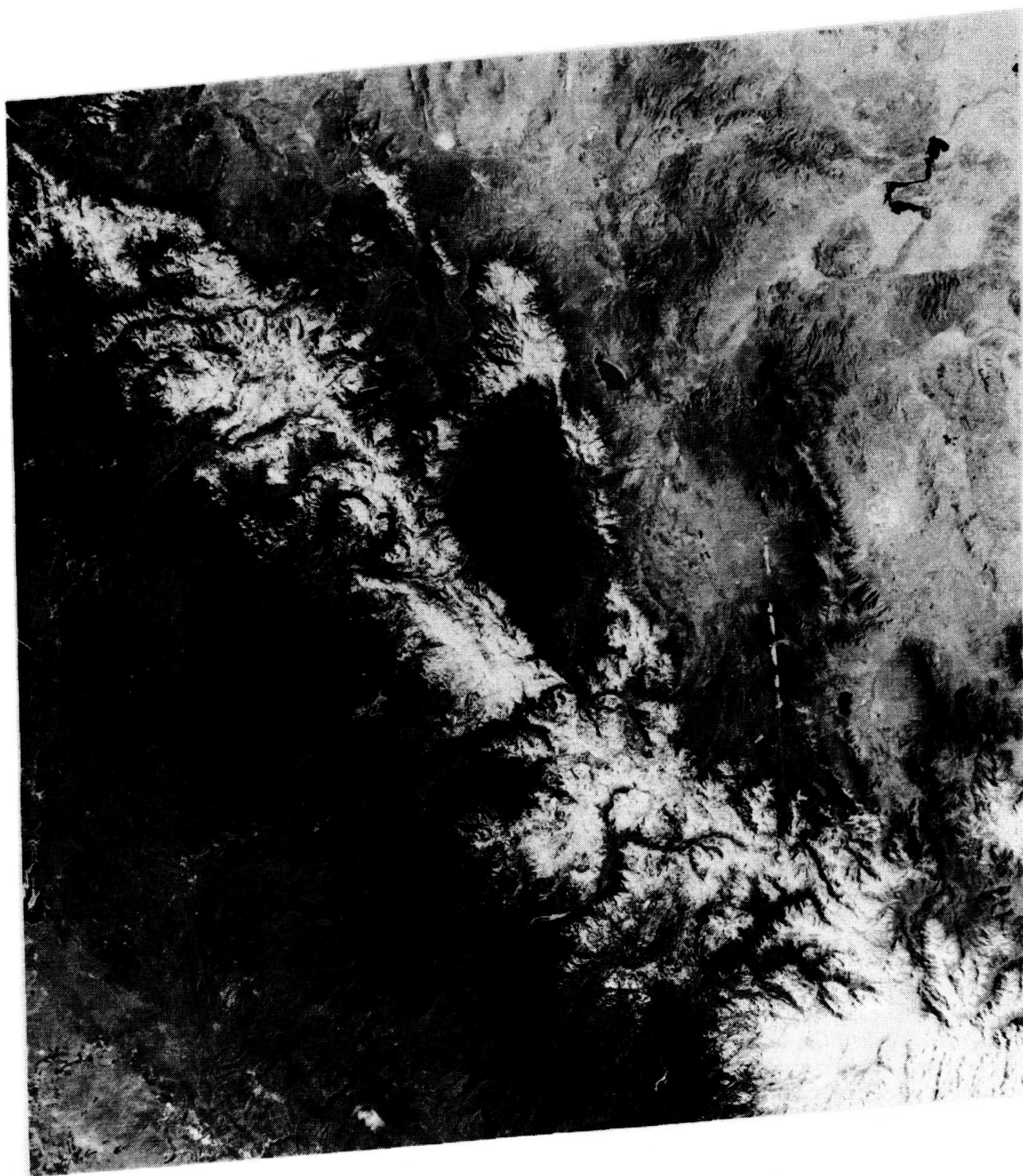
Figure 23.   Landsat MSS-5 image (15 April 1977) viewing the Lake Tahoe area of
the Sierra Nevada during the 1977 severe drought in California.
The snowcovered area surrounding Lake Tahoe can be contrasted with
the more normal amount at about the same date a year later (Fig-
ure 1).

Figure 24a. Landsat MSS-5 image mosaic showing snowcover on the southern
Sierra Nevada, 2 January 1973. The boundaries of the river basins are in-
dicated. Within the Kings Basin, northfacing slopes (such as at A) are in
shadow. Other features include Mono Lake (B), White Mountains (C), and
Owens Valley (D).
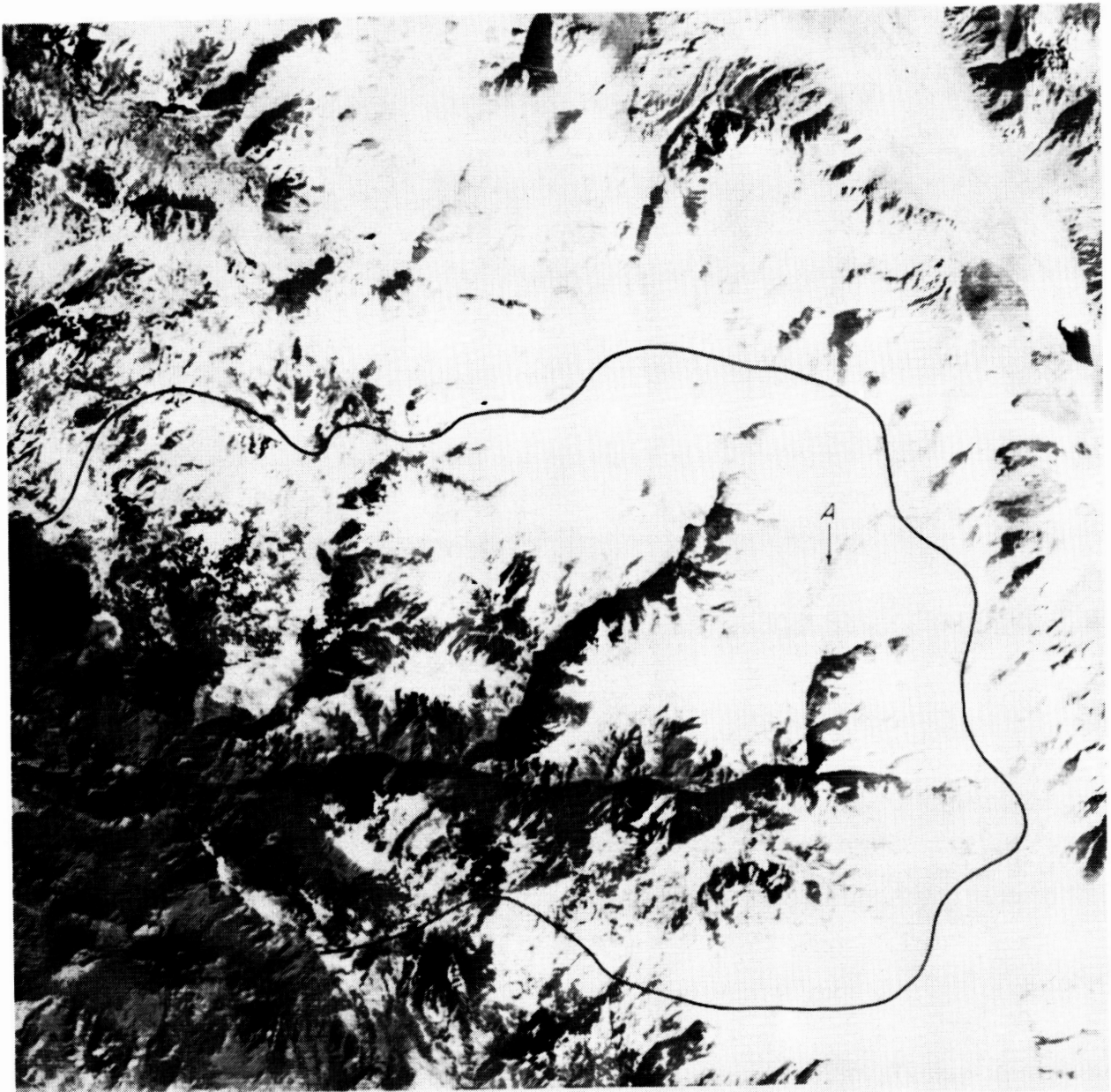
Figure 24b. Reprocessed enlargement of the Kings River Basin area of the image shown in Figure 24a. The shadow effect at A is reduced through the reprocessing.

42

Another method found helpful in monitoring shadow effects on snow fields, snowmelt, and discriminating between cloud and snow, is the generation of high resolution film loops (Reference 33). One-kilometer-resolution GOES sectorized images can be generated every half-hour and spliced together to make film loops that can be run continuously through an appropriate projector.

Manual Snow Mapping Procedures

During the ASVT study program, a number of manual procedures for mapping snowcover were investigated on various watersheds. Each study area utilized, in particular, the Zoom Transfer Scope (ZTS) to map snowcover from Landsat and VHRR imagery. Snowcover maps were also prepared by NOAA/NESS from VHRR imagery, also using the ZTS. Analysts who do not have access to optical mapping devices can map snowcover utilizing other manual procedures, some of which are covered in this section.

Zoom Transfer Scope (ZTS)

The Zoom Transfer Scope (ZTS) was the primary snow mapping tool in the ASVT study program and the standard against which the performance of other techniques was judged. Both Landsat and NOAA/VHRR images were analyzed by personnel at each of the study centers.

In using the ZTS, the image (either a print or a transparency) is superimposed optically onto a base map. Through adjustment of the image projection size and through stretching of the image along either axis, the original image is rectified to fit the scale of the base map. The snow extent can then be mapped directly from a VHRR or a Landsat image, without the use of a gridding system as is necessary for the manual transfer of data to a base map. An example of a snowcover map derived from Canadian "Quick Look" Landsat imagery and the ZTS technique is shown in Figure 25. The map shows about 20% snowcover on the Conejos River Drainage of the Rio Grande Basin in Colorado on 5 May 1977.

Major advantages of the ZTS are its simplicity of operation, relative inexpensiveness, short training time for use, and speed in which mapping can be accomplished. A major disadvantage is the restricted field-of-view requiring several registrations for images of larger drainage basins. Analysts have found that, in general, snow can be identified and mapped somewhat more reliably using Landsat transparencies, rather than prints, with the ZTS.

NOAA/NESS Snowcover Maps

NOAA's National Environmental Satellite Service (NESS) produced satellite-derived areal snowcover maps for selected river basins in each of the four ASVT test sites. The satellite imagery utilized for snow mapping was the NOAA/VHRR (the characteristics of the VHRR are described earlier in the handbook). Snow maps were produced by first registering a VHRR image to a hydrologic basin map. A ZTS is utilized for this purpose. The snowline observed on the image is then traced onto the basin map. The percentage of snowcover for the basin is then determined through use of either a manual or an electronic planimeter. To use the manual planimeter, the area covered by snow is

CONEJOS RIVER
DRAINAGE

COLORADO
NEW MEXICO
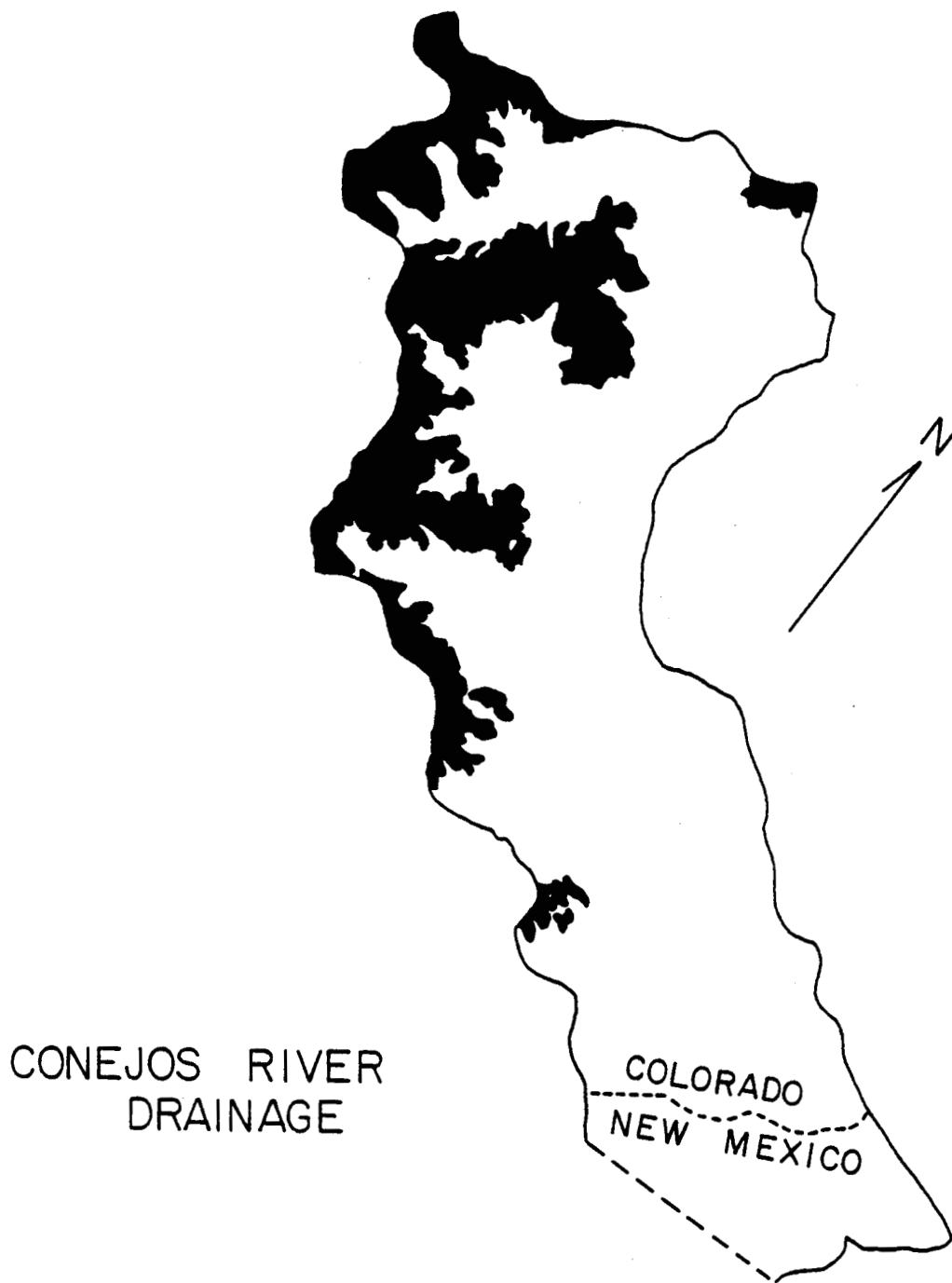
Figure 25. Map showing 20.4 percent snowcover on the Conejos River drainage of the Rio Grande Basin in Colorado on 5 May 1977. Analysis was derived from Canadian "Quick Look" Landsat image (MSS-5).

first measured and then divided by the total basin area. The manual planimeter
works best for basins in which there is a single continuous snowline. In
basins where there are isolated peaks and valleys, such as the Cascade Range,
each snow area must be measured separately and then added together, thus com-
pounding operator error.

Measurements can be made much faster using an electronic planimeter; however,
the operator is obligated to shade in the snow map and prepare a basin sil-
houette or "mask" before using the electronic planimeter. An example of a
NOAA/NESS snowcover map derived from VHRR satellite imagery is shown in Figure
26. This base map shows 14% snowcover for the Rio Grande Basin above the
Colorado/New Mexico border on 23 April 1977.

Mapping Through Other Manual Procedures

A more tedious method to measure the snowline elevation and aerial snowcover
extent of individual drainage basins (percent snowcover) is to transfer the
snow pattern mapped from Landsat or VHRR enlargements directly onto elevation
contour charts. For Landsat, reference can be made to charts from the National
Topographic Map Series (scale - 1:250,000); although the scale of these charts
is larger than that of satellite imagery, charts of this scale are useful for
matching the amount of detail available in the satellite data. In the proce-
dure used, an accurate half-degree latitude-longitude grid overlay is prepared
on a transparent overlay using landmark references. Then, through use of a
variable scale, a fine mesh grid is constructed within each half-degree square
on the transparent overlay. The snow boundaries are traced onto the gridded
overlay, and transferred manually to an indentical (fine mesh grid) transpar-
ent overlay on the corresponding topographic chart, which has an elevation
contour interval of 60 meters (200 feet). The mean snowline elevation is then
determined through measurements at many points along the snow boundary. The
percent area within the basin that is snowcovered can also be determined
through use of a planimeter. An example of this snow mapping technique is
shown in Figure 20. The early May 1973 snowline for the southern Sierras,
shown on this fine mesh grid, is transferred manually to an identical fine
mesh grid overlay on the corresponding topographic chart to determine the mean
snowline elevation.

The California study center reduced Landsat imagery at two different scales, a
direct overlay method and use of the Zoom Transfer Scope. The direct overlay
method interpreted images at a 1:1 million scale, whereas the ZTS interpreted
at a scale of 1:500,000. Comparison of the analyses indicated that although
the ZTS method provided more consistent results, it required considerably more
time than the direct overlay procedure.

Index Baseline Method

As none of the existing snow mapping methods could eliminate the deleterious
effect of cloud cover for direct snowcover measurements in the Colorado ASVT
study area, an indirect approach was investigated. Examination of Landsat
images for mountainous areas of Colorado revealed numerous lines cutting
through drainage basins where the snow surface is visible. Many of these
lines can be connected to form a network that will cover most drainage areas.

14% SNOW COVER

COLORADO

NEW MEXICO

NOT MAPPED
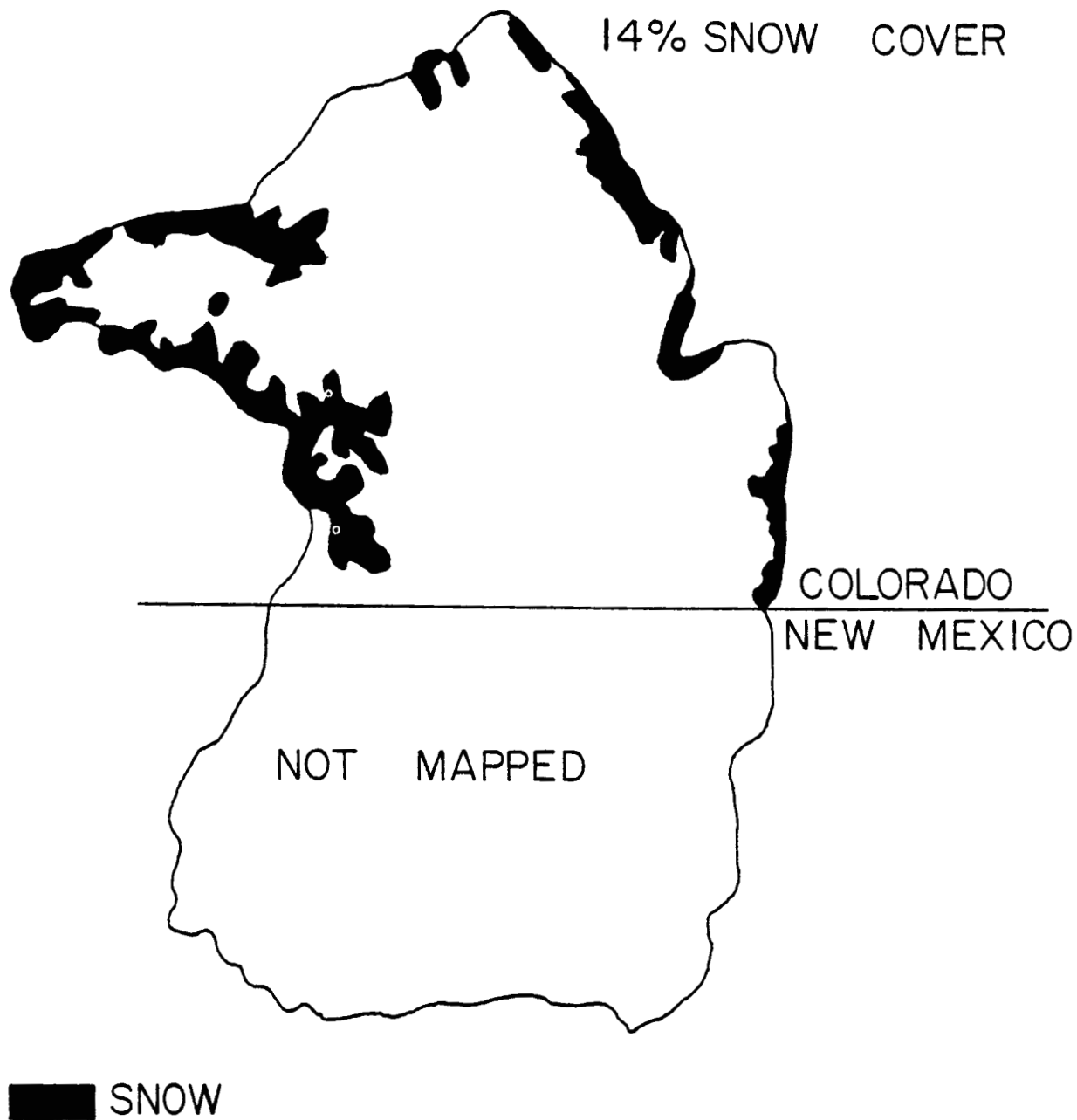
◼◼◼ SNOW

Figure 26. An example of a NOAA/NESS snowcover map derived from VHRR satellite imagery using the Zoom Transfer Scope. This base map shows 14% snowcover for the Rio Grande Basin above the Colorado-New Mexico border on 23 April 1977.

46

Lines visible on Landsat images and clear of obstructions can be used to identify snowline position within a basin. The snowline position has been shown to be indicative of the snow areal extent of a basin where snow recession patterns are repeated.

Estimates of snow areal extent can be made using a baseline network by developing a table of index values relating snowline position on individual baselines to the corresponding snow areal extent of the basin. Once the table of index values has been established, the snow areal extent estimate for a new image is made by locating the snowline/baseline intersections over the baseline network and referring to the table of index values to find the corresponding snow area. Each baseline measurement within a network and the resulting snow areal extent estimate is independent of other baseline measurements and the associated snow areal extent values. Therefore, the greater the number of baseline measurements made, the greater will be the accuracy of the overall estimate.

The advantage of using a network of index baselines is that the network can be constructed to cover the entire basin so that some of the lines are visible even under a relative high percentage of cloud cover. An estimate of snow areal extent can be made even if only a limited number of snowline-baseline intersections can be identified.

The method of indexed baselines was developed on the assumption that within a basin, the snowline recession will follow basically the same pattern year after year. Local variances occur in the pattern due to mesoscale meteorologic influences which include precipitation, wind and temperature. These influences are generally short-term and random in nature, and their effects are temporary causing only minor variations in the snowline recession. For this reason, any given position of the snowline is indicative of the total snow areal extent over the basin at the time of measurement.

Once the snowline recession patterns have been established for a drainage basin, a network of indexed baselines can be devised that accurately describes the snowline recession. Selection of lines for an indexed baseline network should conform to a definite set of criteria. In the Conejos drainage basin, a number of different terrain features were found suitable for index baselines. In nearly all cases, the index lines consist of areas of bare ground or very low ground cover. These clear areas include roads, avalanche paths, clearcuts, landslides, and stream courses.

Index values relating snowline recession to snow areal extent of a basin are straight line distances measured from the snowline/baseline intersection to the terminal point of the baseline. The following operations must be performed on each image to determine index values for the baseline network:

(1) interpret and outline snow areas;

(2) measure total snow area of the basin;

(3) superimpose network of baselines over the image; and

(4) make baseline distance measurements in millimeters from

the snowline/baseline intersection to the baseline terminal point for each baseline.

Operations (1) and (2) are only performed in order to build the table of index values. Once the table has been established, the only image interpretation required to make a snow areal extent estimate is that of identifying the snowline/baseline intersections.

Comparison with Aerial Survey

Aerial observation of snowcover distributions can provide valuable information during periods of cloud cover that preclude satellite snowcover observations. Aerial snow surveys or aerial photography were acquired for each of the four ASVT study areas.

In Arizona, approximately seven or eight aerial reconnaissance flights are flown each winter over the Salt-Verde watershed during the period from about early January to mid-April. These flights collect information on snow depths, as well as the aerial distribution of snowcover. Maps of snowcover distributions are prepared using visual mapping techniques to assist in the analysis of satellite imagery. The value of aerial observations and visual mapping of snowcover distributions are clearly demonstrated during storm periods when excessive cloud cover often prevents effective satellite observations of snowcover distributions. Snowcover distributions mapped by experienced observers are generally in close agreement with the snowcover distributions shown in Landsat imagery.

Estimates of snow depths at selected sites in the upper Salt River watershed are obtained through use of oblique 35 mm color photography of aerial snow markers taken during reconnaissance flights. Estimates of snow depths have been found to be more easily obtained from an evaluation of the shadow of the aerial snow marker than from the vertical marker itself.

Aerial observations began in California during the heavy snow season of 1952, when the U.S. Army Corps of Engineers (Sacramento) initiated observations of snowcovered area from low flying aircraft in the southern Sierra Nevada. This was done in connection with the operation of reservoirs during the period of snowmelt. Initial work was done in the Kings River Basin for operation of Pine Flat Reservoir. Observations extended into the Kern River in 1954, and eventually included the Kaweah and Tule River Basins. Observations were taken more or less routinely during the period of major snowmelt. The program continued for about 20 years until 1973.

During 1978, the Corps resumed aircraft observations in the southern Sierra as the result of the unusually heavy snowpack conditions and potential for spill of snowmelt runoff from reservoirs. Information on snowcovered area (SCA) for estimation of both rate and volume of snowmelt runoff was obtained from aircraft and satellite. In many cases, aircraft observations varied considerably from the satellite observations. Figure 27a delineates the snowcovered area in the Kings River Basin during the 1973 season as derived from Landsat imagery, NOAA imagery, and aircraft observations. Figure 27b delineates snowcovered area during the 1978 season, including Canadian Quick Look Imagery.

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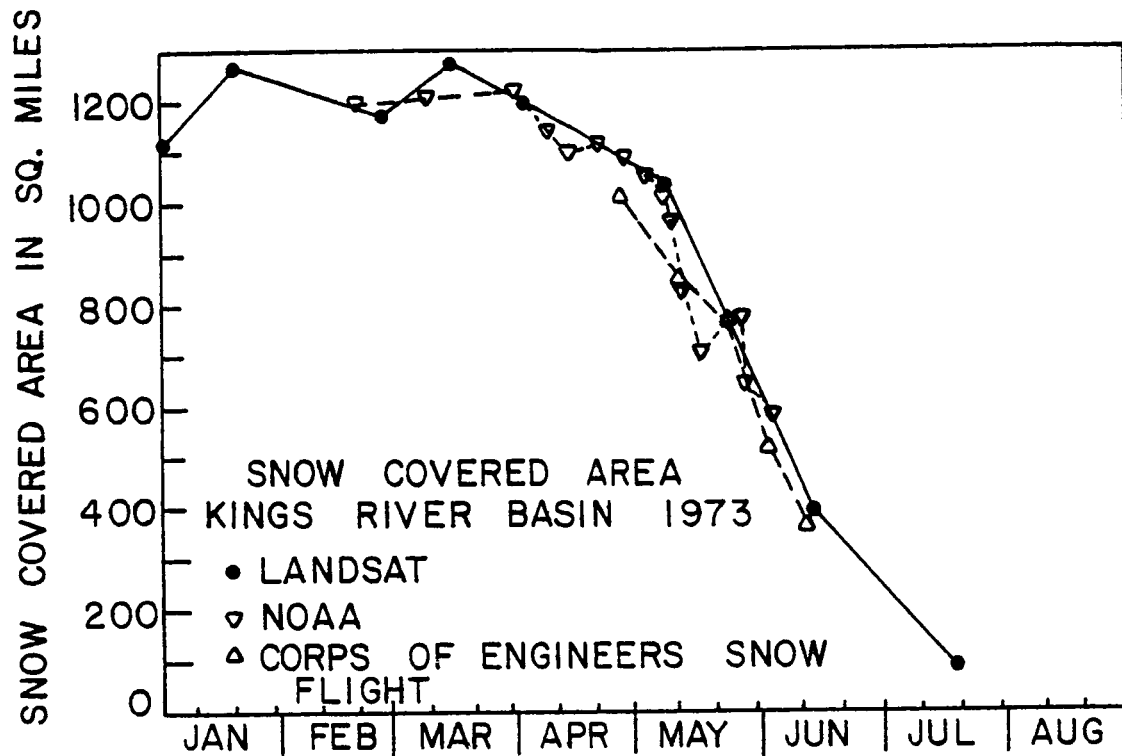
Figure 27a. Graph depicting snowcovered area in the Kings River Basin
during the 1973 season as derived from Landsat imagery, NOAA imagery,
and aircraft observations.
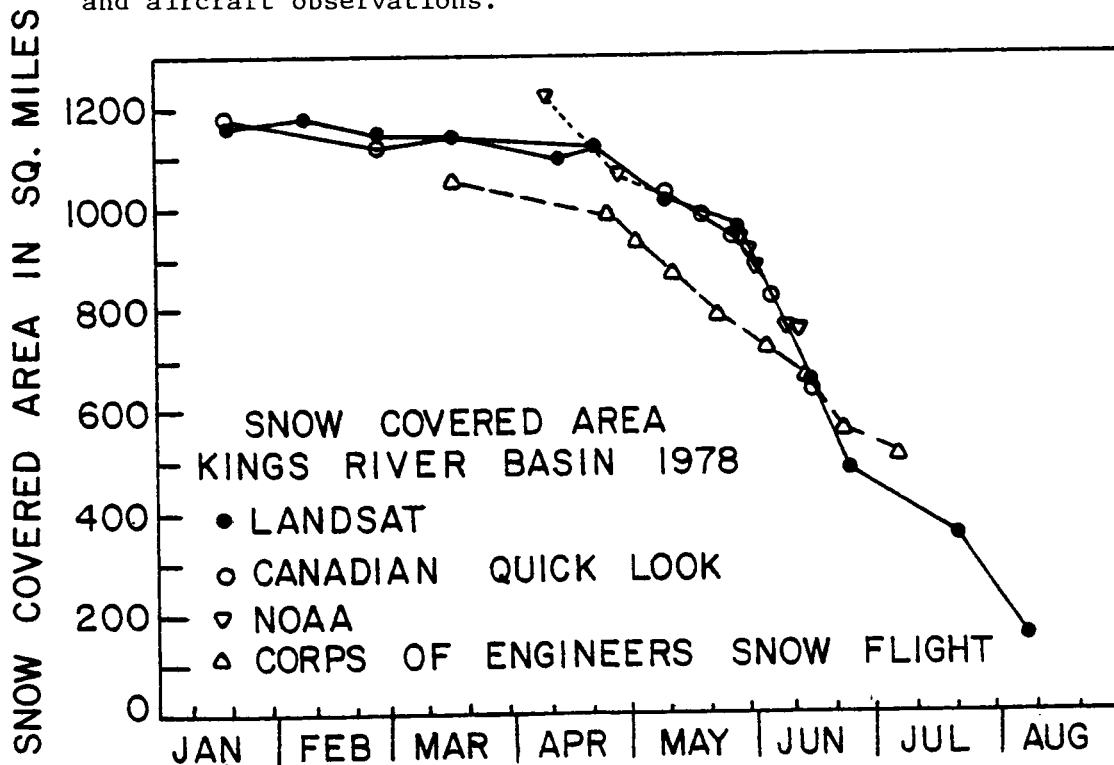
Figure 27b. Graph showing snowcovered area in the Kings River Basin
during the 1978 season as derived from Landsat imagery, NOAA imagery,
Canadian Quick Look imagery, and aircraft observations.

49

The Corps of Engineers attributes the difference between aircraft observations and satellite SCA to the following possible causes:

(1) aircraft observers delete patches of snow that are below the major unbroken snowpack;

(2) aircraft observers try to delete areas of fresh light snowpack which do not represent the major winter accumulation; and

(3) aircraft observers and methods change at various times.

In the Colorado study area, low altitude aerial photography was acquired from a light aircraft using a handheld 70 mm Hasselblad 500 EL/m with a 100 mm lens. Aerial photography was first used in the program in April 1976, and again during the 1978 snow season. The photography was intended to aide in interpreting Landsat images and for documentation of specific problem areas for various snow conditions. Low altitude oblique aerial photography proved valuable in resolving the following problems: snow under coniferous tree cover, shadow areas in deep canyons and on north aspect slopes, landslide areas and bare boulder fields, and in deciduous forest (aspen) where thick bare trees caused a shift in grey tone to resemble rock or bare ground.

During the 1978 snow season, aerial photography was used in conjunction with the Index baseline method to estimate snowcover for the Conejos River Basin. Two estimates of snowcover were made 3 April and 13 April. Aircraft estimates were consistently lower than standard Landsat snow mapping measurements, but were sufficiently accurate for use in most analyses.

In the Northwest study area, snowcover observations are made in the United States portion of the Columbia River Basin by the Corps of Engineers personnel in small aircraft flying at a low altitude. Similar flights are made in the Canadian portion of the basin by personnel from the British Columbia Hydro and Power Authority. In these snow flights, an experienced observer riding with the pilot looks out the window at the snowline, determines its elevation, and then plots the snowline on a map as the flight is made. At the end of the flight, this information is reduced to percent of basin which is snowcovered. Although the observers on these flights are experienced, the data gathered are entirely subjective, and the snowline which is traced excludes the lower lying patchy snow which is not considered to contribute to runoff. Two to four flights are generally made each season for each area depending upon the flood potential for that season, flying conditions, and the cloud cover over a basin. In the United States portion of the basin, flights are generally made in April, May and June; and in the Canadian portion, in May and June.

Machine Processing Techniques Using Imagery and Digitized Data

Density Slicing

In this snow mapping procedure, a positive Landsat transparency is placed on a light table with an opaque mask covering all but the drainage basin to be

mapped. A camera records the various shades of grey and breaks them down into
twelve (12) discrete levels which are displayed on a monitor in 12 false
colors. Single or multiple colors which the operator thinks matches what he
believes to be the snowcovered area are electronically planimetered and
reported as a percent of the basin area. A major advantage of this system is
the speed with which a basin can be mapped. Unfortunately, in basins having a
dense forest cover, it is difficult to distinguish snow under trees; errors
also arise from highly reflective surfaces such as boulder fields above timber-
line which appear much like snow to the machine. Reliable mapping and inter-
pretation of results is dependent upon the operator's familiarity with the
basin. At best, the system is prone to a rather high degree of machine error,
as well as error induced by operator decision on snow classification relative
to the 12 discrete mapping colors.

Color Additive Viewer

A color additive viewer which uses four 70 mm transparencies (chips) coincid-
ing with Landsat MSS bands 4, 5, 6 and 7, can be utilized to map areal snow
extent. In this procedure, the four chips are registered with one another to
produce either a false color infrared composite or a natural color composite
at a scale of 1:500,000. A mylar overlay base map is then used for manually
mapping the snowcovered area. The snow areal extent is then either computed
by hand planimeter or an electronic planimeter such as that found in the den-
sity slicer. Time requirements for mapping and interpretation are similar to
the Zoom Transfer Scope. Major advantages of this technique are its ease in
setting up and producing snowcover maps, and the relatively short time period
required to receive the 70 mm chips (two to three weeks earlier than standard
Landsat imagery). The major disadvantage of this system is the relatively
high cost of the instrument.

Interactive Computer System

In another study (Reference 34) utilizing an interactive computer data access
system (McIDAS), the extent of snow fields were measured in the Salt and Verde
River Basins in central Arizona from satellite images. This study was based
on real-time visible image data of 1 km resolution generated by the eastern
GOES. This method for preparing snowcovered areas (SCA) was compared to the
current operational SCA techniques used by the National Environmental Satellite
Service (see section on manual snow mapping procedures). The GOES/McIDAS SCA
results showed good agreement when compared with the NESS products during the
period from 10-15 January 1977. However, during the period from 16-28 January
1977, the GOES/McIDAS products showed about three to five percent less snow-
cover than the NESS products.

Computer Assisted Classification

As reported by Schneider (Reference 33), an additional project is underway at
NESS to check the feasibility of doing all digital snow mapping using 4-km
visible GOES data. The test area includes nine contiguous basins in the
Sierra Nevada. These basins offer a wide variety of terrain characteristics
and ground cover for control purposes; they are also of ideal size and loca-
tion as viewed from the western GOES satellite. Data used in this experiment

are stored on computer disk packs for 24 hours. The model involves the thresholding of each individual basin pixel for snowcover and takes into account solar illumination angles as well as the nature of ground cover. A detailed description of this snow mapping model, as well as preliminary results for the 1978-1979 snow season, are presented in Tarpley et al (Reference 35).

Digital computer techniques were also investigated during the ASVT study using computer compatible tapes (CCT's) of Landsat images. These computer techniques were completed on the Image 100 interactive system and on the CDC 6400 computer to produce grey-scale maps of snowcovered terrain. Both computer processes required considerably more effort than any other procedure attempted. Once appropriate CCT's are obtained, it is necessary to combine, sample, geometrically correct and register them to a specific watershed prior to analysis. The Image 100 utilizes a so-called supervised classification mode employing "training sets" selected by the operator to teach the computer to recognize terrain covered by snow. The computer operator/interpreter through his prior knowledge of what constitutes snowcover in a specific basin is invaluable in producing a reasonable snowcover estimate. The analysis of the CDC 6400 data involves a slightly different approach than the Image 100. This method relies upon a semi-supervised classification scheme incorporating user defined confidence intervals for classifying groups of spectral data as snow or non-snow, according to algorithms specifying upper and lower grey-scale boundaries.

Both the Image 100 and CDC 6400 analyses are awkward and expensive in terms of time and money for the tests conducted. From an operational point of view, it does not appear that this method lends itself well to timely and accurate snow mapping. Nevertheless, computer assisted snow classification offers considerable promise for future automated snow analysis, especially for multiple basin snow mapping, and a number of studies are continuing (such as reported in Reference 36).

TECHNIQUES TO INCORPORATE SNOWCOVERED AREA INTO OPERATIONAL WATER MANAGEMENT PROCEDURES

Discussion of Empirical Techniques for Relating Snowcovered Area to Runoff

Operationally useful information on either the depth or water equivalent of mountain snowpacks cannot be derived from currently existing satellite systems. The question of how to relate satellite observations to runoff prediction has, therefore, been of prime concern. At the time that techniques to map snow from satellite data were being developed, other research related to runoff prediction was being carried out using aerial photographs. In studies of certain Colorado watersheds, Leaf (References 10 and 11) found that a functional characteristic existed between extent of snowcover during the melt season and accumulated runoff, and that snowcover depletion relationships were useful for determining both the approximate timing and the magnitude of seasonal snowmelt peaks. This research provided the basis for later studies to relate satellite snowcovered area to snowmelt runoff.

Studies to employ satellite snowcover observations for seasonal streamflow

estimation were conducted by Rango et al (Reference 37). The initial attempts were made using low resolution meteorological satellite data to map snow-covered area over the upper Indus River Basin in Pakistan. For the Indus River, early spring snowcovered area was extracted and related to April through June streamflow from 1967-1971 using a regression equation. Prediction of the April-June 1972 streamflow from the satellite data was within three percent of the actual total.

The results of further studies for two years of data over the Wind River Mountains in Wyoming indicated that Landsat snowcover observations, separated on the basis of watershed elevation, could also be related to runoff in significant regression equations. The relationship between percent snowcover and runoff for the four lower elevation watersheds is shown in Figure 28. From these results, Rango et al (Reference 37) concluded that satellite-observed snowcovered area could be usefully employed as an additional seasonal runoff index parameter or as an input into certain hydrologic models.

Another empirical approach for relating snowcovered area to runoff was reported by Thompson (Reference 38). In this approach Landsat images were used to map snowcover depletion for three snowmelt seasons on a small watershed in southeastern Wyoming. The results indicated that the use of a snow-covered area as a forecasting index of total runoff was not promising; for example, the actual snowcovered areas for given dates in 1973 were the same or exceeded the areas for similar dates in 1974, although the total 1 April - 31 July runoff for 1973 was only 716 m^3/sec (25,300 cfs) as compared to 917 m^3/sec (32,393 cfs) for 1974.

Far more promising results for the use of Landsat snow mapping for total run-off forecasting were obtained in comparing basin snowcover percentages to accumulated runoff to dates of the Landsat scenes (Reference 38). For better comparison between yearly melt seasons, the parameters were made dimensionless with X = snowcover/total basin area and Y = accumulated runoff/total April 1 - July 31 runoff. Although the individual snowcover depletion curves vary considerably for each year, the dimensionless depletion-accumulation curve, shown in Figure 29, was found to hold for each of the test years regardless of varying weather conditions, depth of snowpack, water equivalent of snowpack, and total runoff. Furthermore, whereas the dimensionless curve established may be unique to a single basin, the availability of Landsat data makes the development of similar curves for any number of basins simple and relatively inexpensive.

Snowcover depletion curves have also been derived for the river basins of the Colorado ASVT study area using a larger data sample (Reference 39). All usable images in the March - June meltout period were used to produce the snowcover depletion curves, which depict the gradual loss of watershed snowcover during the primary melt season. Although the curves were developed from only six years of data, they represent a fairly wide spectrum of hydrologic conditions. Curves for two basins are shown in Figure 30 (a and b).

Examination of the snowcover depletion curves shows a melt sequence that is similar from one year to the next, resulting in roughly parallel curves. The displacement of the curves with time in different years is directly related to

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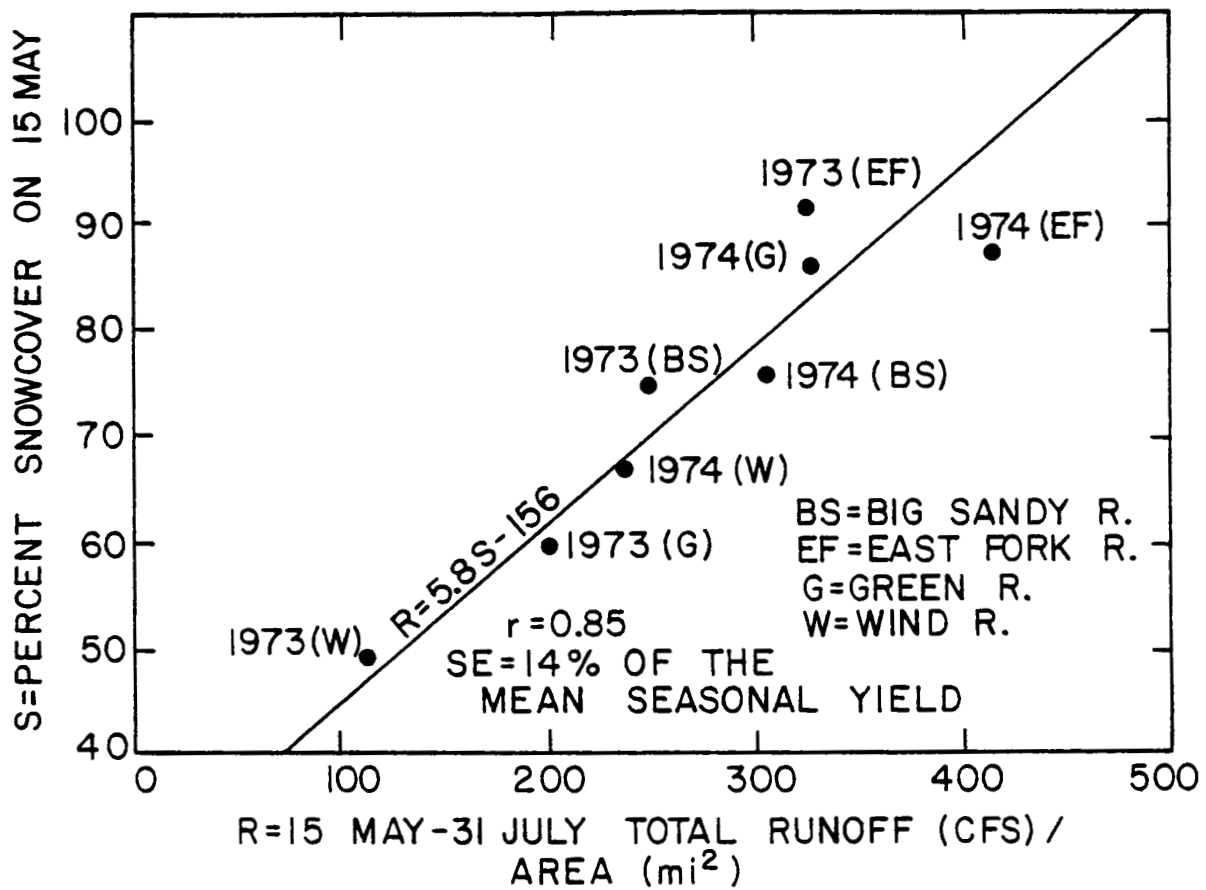
Figure 28. Landsat derived snowcover estimates versus measured runoff (1973 and 1974) for four watersheds less than 3,050 m mean elevation in the Wind River Mountains, Wyoming (after Rango et al, 1975).
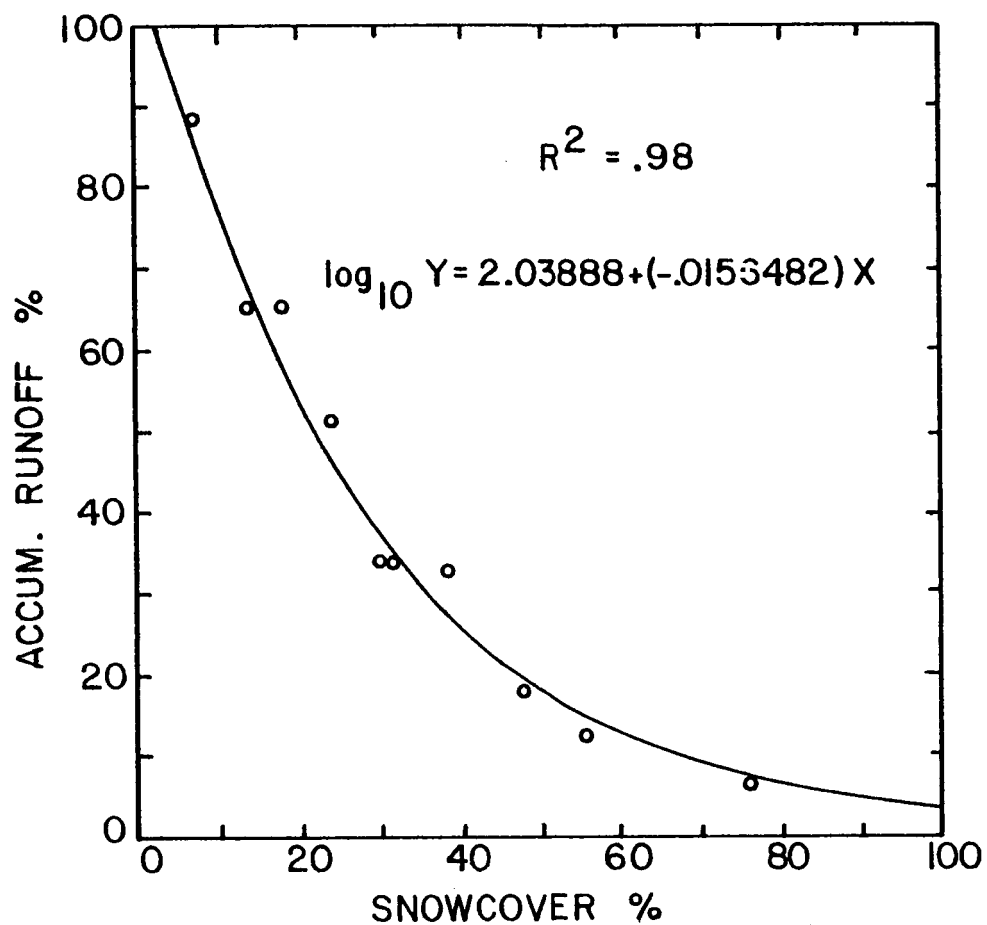
Figure 29. Dimensionless depletion-accumulation curve showing composite snowcover plotted versus accumulated runoff (after Thompson, 1975).
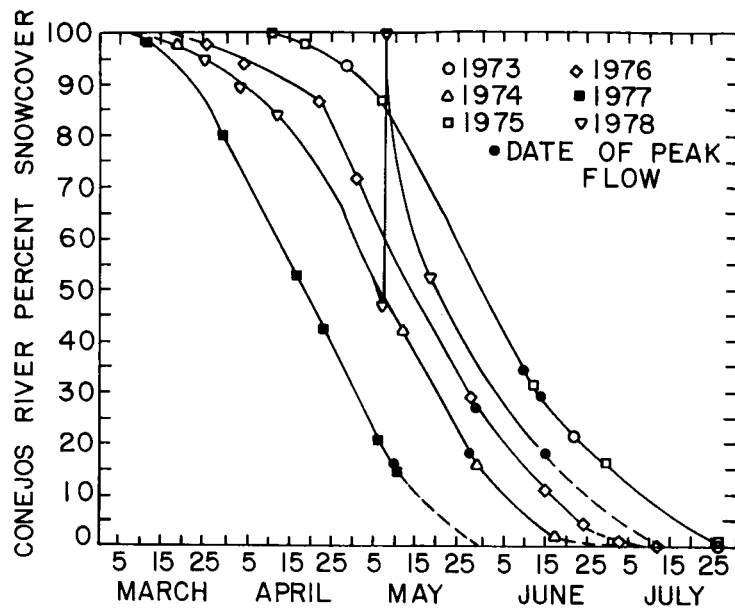
Figure 30a. Snowcover depletion curves for Conejos River.
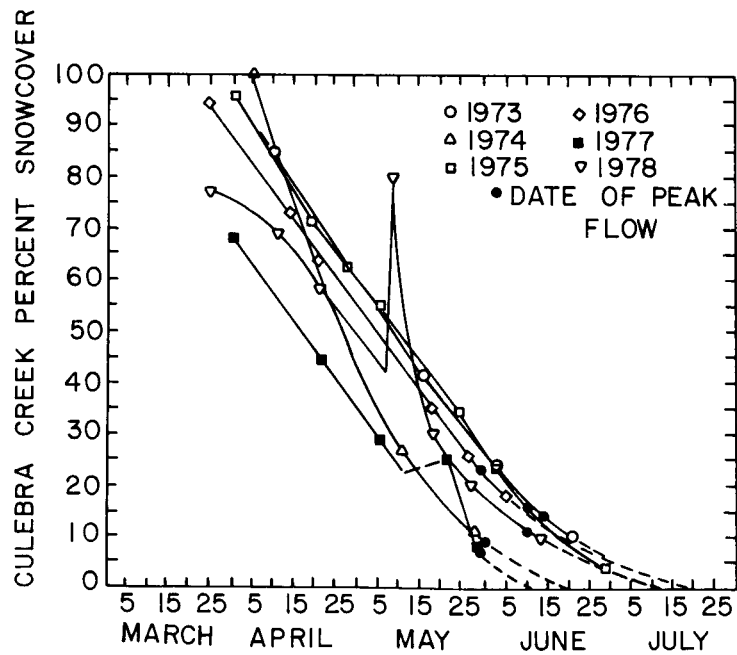
Figure 30b. Snowcover depletion curves for Culebra Creek.

the amount of water stored in the snowpack. In low snowpack years, melting begins and ends earlier, resulting in reduced runoff. In high snowpack years, the onset of melt is initially retarded owing to the depth of the snowpack and the increased energy requirement necessary to bring the pack to isothermal conditions. Meltout and the corresponding runoff are prolonged accordingly. Snow areal extent during the main melt period is a good measure of the water stored in the snowpack and the volume of runoff likely to be produced. This relationship appears to be valid except when large scale late season storms significantly alter the watershed mean areal water equivalent. Such an event occurred on May 8, 1978; Figure 30a shows the effects of the storm in the form of displacing the snowcover depletion curve in time from where it would normally have been (the Landsat images before and after this snowfall event are shown in Figures 17 and 18).

In a study carried out at the California study center (Reference 22), the potential value of satellite snowcovered area in runoff predictions was tested for two watersheds in the southern Sierra Nevada, the Kings and the Kern, using simplified linear multiple regression analyses. In order to increase the sample size, aircraft visual observations of SCA were used in addition to satellite observations; the combined period of record, therefore, was 25 years on the Kings River and 23 years on the Kern. The indices used for development of the forecast procedure were the following: snowpack index based on the observed water equivalent at approximately 20 snow courses in each basin as of 1 April; October to March precipitation index; April to June precipitation index; October to March runoff index; and previous year runoff index.

One of the analyses carried out was to observe the effect of snowcovered area (SCA) in improving forecast reliability. In this analysis, conventional procedures were used to prepare the 1 April forecast procedure; then procedures were developed for 1 May and each subsequent date, with and without SCA as an input. The results, shown in Figure 31, indicate that the addition of SCA as a parameter seems to offer little improvement in procedural error during the melt season for the Kings Basin; for the Kern Basin, however, the addition of SCA results in a substantial reduction in standard error as the season progresses.

The relatively inconsistent relationship between precipitation, snowpack accumulation, elevation, and location within the Kern River watershed described previously may be one of the more important reasons why SCA represents an effective parameter in updating Kern forecasts. The Kings River has a much more uniform area-elevation distribution than the Kern River. It appears, therefore, that snowcovered area will be most effective in reducing forecast procedural error on watersheds with: (1) a substantial amount of area within a limited elevation range; (2) an erratic precipitation and/or snowpack accumulation pattern not strongly related to elevation; and (3) poor coverage by precipitation stations or snow courses restricting adequate indexing of water supply conditions.

Description of Models With Which Snowcovered Area Can be Used

In addition to the empirical approaches described above for relating snow-covered area to runoff, each ASVT study center also tested methods for incor-

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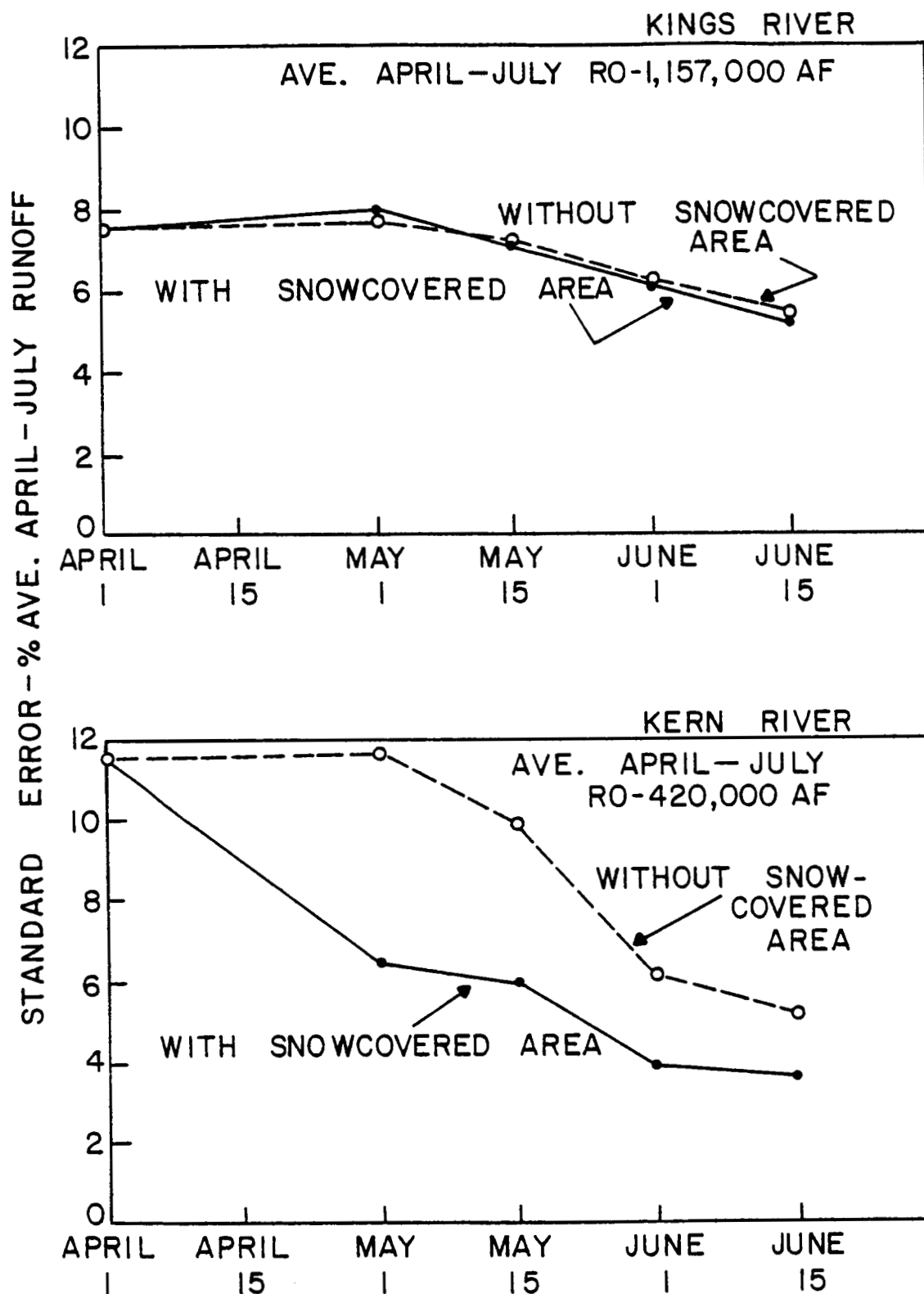
Figure 31. Graph showing standard error of forecast procedure (with and without snowcovered area) versus date during snowmelt.

porating satellite data into runoff prediction models. The techniques which were most advantageous to the specific needs of their particular area were utilized. The following sections describe the runoff prediction models that were tested.

California

The California Department of Water Resources currently operates, for water management purposes, a hydrologic model to simulate daily runoff on the Kings River Basin given observed conditions of daily precipitation, temperature, and other hydrologic parameters. The existing model consists of five basic sub models of varying complexity and influence on the overall hydrograph. The submodel of primary concern in the ASVT study was that related to snowmelt flow.

Techniques using snowcovered area (SCA) as a parameter to estimate the rate of snowmelt contribution as input to the Kings River hydrologic model were developed. Although previous investigation leading to the Kings River model suggested that areal extent of snowcover influences rate of snowmelt runoff, the technique had not been developed to incorporate this parameter into the operational model. Utilization of SCA required a relationship between the rate of snowmelt contribution to the runoff hydrograph and temperature, SCA, and related parameters which would permit simulation of daily snowmelt runoff from the hydrologic model. The original snowmelt submodel was completely removed from the hydrologic model and replaced by the SCA submodel, since the basic techniques used in the two submodels differed conceptually. The basic data used as input to the SCA snowmelt submodel and the Kings River hydrologic model are shown in Figure 32. Simulated mean daily runoff for the Kings River computed as output from the model have been plotted for the 1973 snowmelt season in Figure 33.

Analysis of melt volume and melt rate during the period of snowpack priming is complicated by the fact that the snowpack is not fully primed throughout the watershed, and therefore, the watershed is not capable of producing runoff from the entire snowcovered area, no matter what the temperature. It has been assumed for purposes of the model that the watershed produces no snowmelt runoff above the "elevation of prime" and all of the runoff required to meet the observed hydrograph of snowmelt runoff comes from the area of the watershed which is snowcovered below the effective "elevation of prime". It was assumed that a given set of temperature and snowcovered area conditions would produce snowmelt volume equivalent to that derived from specific elevation zones, and that any reduction or difference between the calculated and observed melt was attributable to the fact that no runoff occurred above an "elevation of prime", regardless of temperature.

To develop systematic relationships to describe the "elevation of prime", the basinwide melt was calculated from the melt derived for specified elevation zones. Next, the volume of daily melt required to reproduce the observed hydrograph was estimated. The difference between the calculated and "observed" melt volumes was then used to determine the elevation above which no snowmelt could occur if the "observed" runoff hydrograph were to be realized from "calculated" melt. This elevation was defined for purposes of the SCA snowmelt model as the effective "elevation of prime". The elevation of prime was then defined

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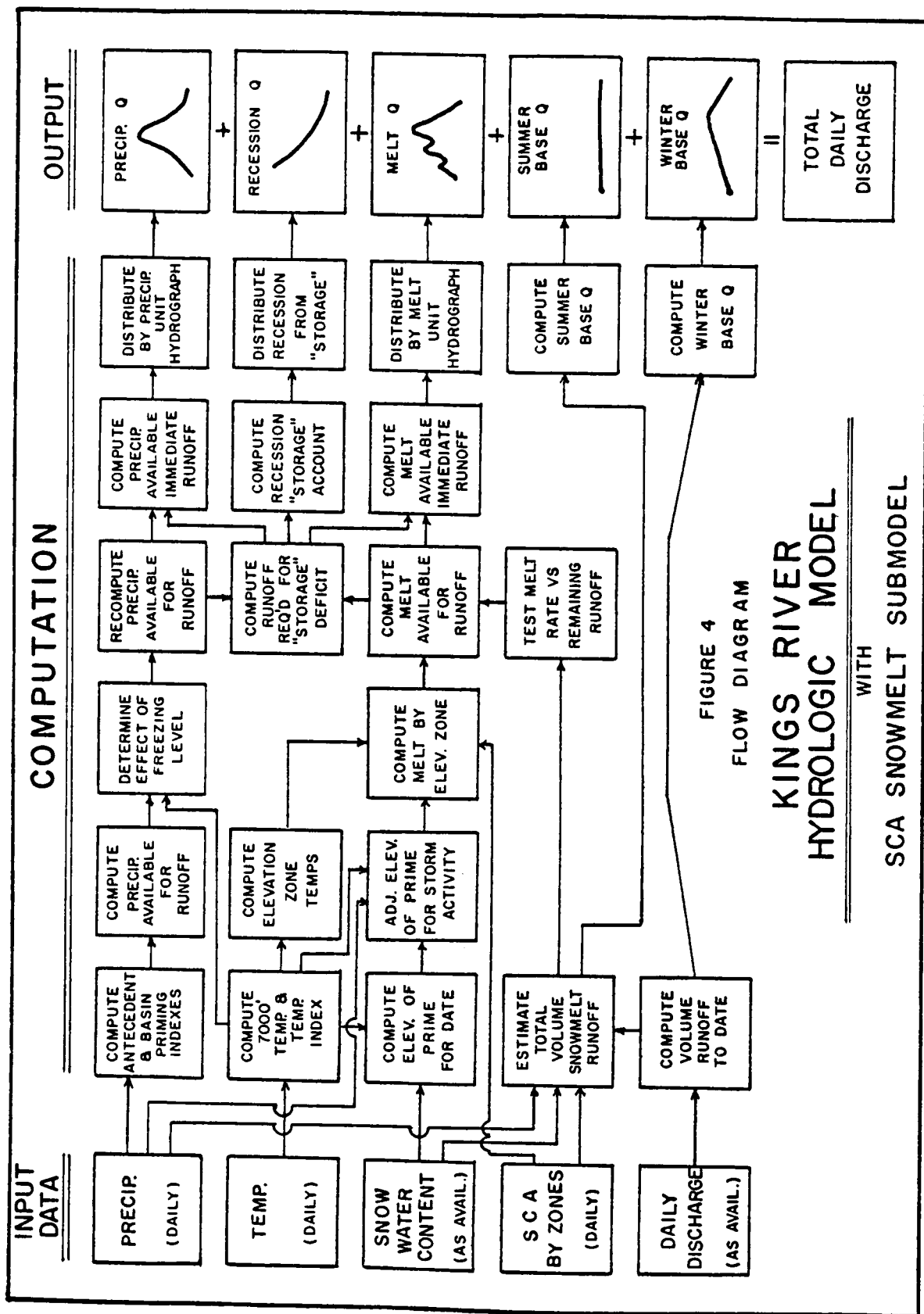
Figure 32.   Flow diagram of the Kings River Hydrologic Model and the SCA snowmelt submodel.

FIGURE 5

KINGS RIVER HYDROLOGIC MODEL
SNOWMELT SUB MODEL

COMPARISON OF OBSERVED
AND CALCULATED FLOWS
1973 SEASON

ACTUAL FLOW
CALCULATED FLOW
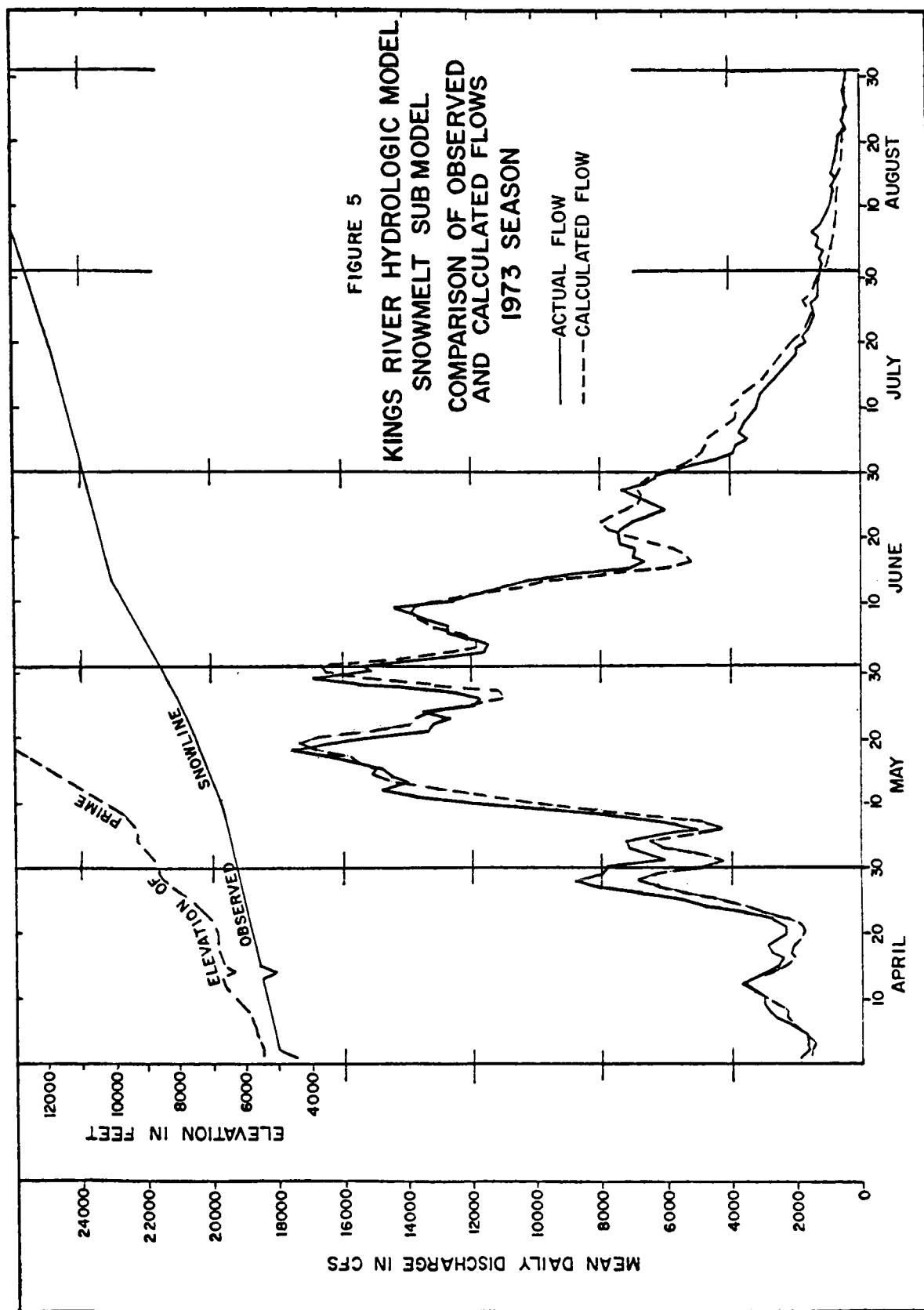
Figure 33. Graph showing comparison of actual flow and calculated flow derived from the Kings River Hydrologic Model for the 1973 snowmelt season.

in terms of other measured or calculated parameters considered related to the priming process. Many combinations of parameters were tested to establish a relationship between "elevation of prime" and the following factors were chosen:

Temperature – A decayed accumulative temperature (0.96 daily decay factor) was based upon the accumulation of degree days above freezing at 7000 feet from January 1. This factor represented a measure of the accumulation of energy to which the snowpack might be subjected as reflected by air temperature.

Date – The date of the season also appears to reflect some measure of energy introduced to the snowpack that would be somewhat independent of temperature.

Snowpack Water Content – April 1 snowpack water content (expressed in percentage of average April 1 water content) updated for subsequent precipitation, was used to describe the amount of snowpack which must be primed before runoff would occur. The greater the water content of the snowpack, the slower the elevation of prime would rise.

The basic equation for computation of elevation of prime for the Kings River SCA snowmelt submodel took the following form:

$$E_p = 3.1 \times K \times (1.009)^D + .017 \times K \times (T1-100/K)$$

where: E_p = the elevation of prime in 100 feet;

D = number of days since February 1;

$T1$ = decayed accumulated temperature (degree days at 7000 feet) since January 1 with a decay factor of 0.96; and

K = a variable affecting the elevation of prime as related to snowpack water content (HSI). K decreases with increasing HSI.

The resulting elevation of prime is the maximum elevation to which the watershed is capable of producing snowmelt runoff (for purposes of model computation) as of the give date.

Colorado - Subalpine Water Balance Model

In Colorado, the Subalpine Water Balance Model developed by Leaf and Brink (References 40 and 41) is being used for making and updating residual streamflow forecasts. Updating of this model during the snow accumulation season is accomplished by means of the SCS Snow Telemetry (SNOTEL) data acquisition system. During the snowmelt season when snowcover on the watershed is less than 100 percent, forecasts are revised on the basis of percent snowcover and associated residual water equivalent.

The Subalpine Water Balance Model was developed by the USDA Forest Service to simulate daily streamflow. This model simulates winter snow accumulation, the shortwave and longwave radiation balance, snowpack condition, snowmelt and subsequent runoff on as many as 25 watershed subunits. Each subunit is described by relatively uniform slope, aspect, and forest cover. The simulated water balances on each subunit are compiled into a "composite overview" of an entire drainage basin.

Detailed flow chart descriptions and hydrologic theory have been published (References 40 and 41). A flow chart of the system is shown in Figure 34. Operational computerized streamflow forecasting procedures which utilize the Subalpine Water Balance Model are keyed to real-time telemetered snowpack (SNOTEL) data and satellite imagery. Satellite systems such as Landsat and near real-time data acquisition systems like SNOTEL are used to update the model at any time by means of "control curves" for a given drainage basin which relate satellite snowcover data to residual water equivalent on the basin, and SCS SNOTEL data to area water equivalent on the basin. Using these relationships, simulated residual volume streamflow forecasts can be revised as necessary to reflect the current meteorological conditions and amount of snow. The Subalpine Water Balance Model was also calibrated to several index watersheds in the Rio Grande and Arkansas River Basins (Reference 39).

Northwest

Daily operational runoff forecasts for streams in the Pacific Northwest are made using the Streamflow Synthesis and Reservoir Regulation (SSARR) computer model. At the beginning of each spring snowmelt season, usually late March or early April, the model is initialized. Values for the model parameters such as snowcovered areas, seasonal volume, soil moisture, initial melt rate, and baseflow infiltration are estimated from all available information. The model is run daily and model parameters are adjusted until the forecast and observed hydrographs match within a certain tolerance. Reliable estimates of basin snowcovered area are extremely important during this initial adjustment period.

The SSARR model adjustment routine, to a large degree, identifies those basins which are not computing properly. Routinely, during the spring snowmelt period, the model is backed up two days and run with observed temperature and precipitation data for that two-day period. The model begins with an observed flow and a set of initial conditions and iterates to hit an observed flow two days later, within a certain tolerance. In the iteration routine, the moisture input (snowmelt plus rain runoff) to the model is multiplied by a factor ranging between 0.5 and 2.0 until the current flow is matched within the specified tolerance. The final adjustment factor for each watershed is listed for each run. Those factors are entered daily on the hydrograph and a history of an individual basin's performance is developed.

A series of adjustment factors less than 1.0 or greater than 1.0 indicate that the parameters for that basin have some bias and need to be inspected. Snowcovered area is one of the parameter values that might be changed to improve the performance of an individual basin. An additional aspect of this adjust-
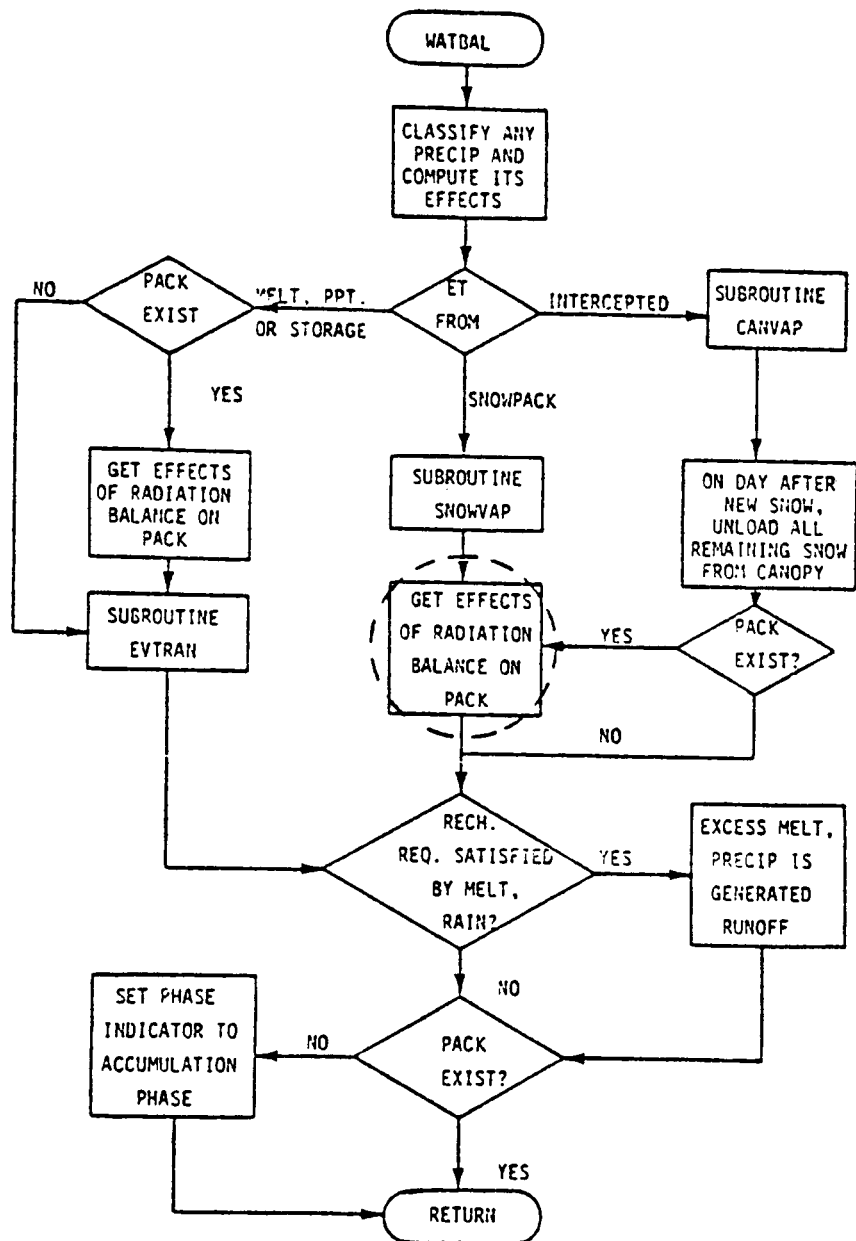
Figure 34. Flow diagram of the Subalpine Water Balance Model.

ment routine needs to be considered here. Often, the watershed adjustment factors may be near 1.0, indicating that the basin parameters are in proper adjustment. A satellite snowcovered area report may be received which shows a snowline different than that carried in the model. In general, when this occurs, only a token adjustment is made in the model unless some compensating parameter changes can be made to continue the good fit for that particular watershed. Conversely, when the SCA carried by the model and a satellite SCA are disparate, and the basin adjustment factors indicate that a change to the snowcovered estimate would improve the model's fit, the satellite estimate would be used to directly update the basin parameter.

Other Models

A snowmelt-runoff model has been developed on the basis of experimental measurements in two small mountain watersheds of central Europe (Reference 42). In a recent study, the model was applied to simulate the snowmelt-runoff in the Dinwoody Creek Basin in west central Wyoming, a basin significantly larger than those on which it was developed. The changing areal extent of the seasonal snowcover is an essential variable in this procedure.

Three variables need to be currently assessed for model calculations of daily snowmelt-runoff, namely, snowcovered area, temperature (degree days), and precipitation. The snowline is traced on satellite images across the entire watershed and the snowcovered area is planimetered manually in each of the four 500 meter elevation zones comprising the watershed. These analyses are used to construct a snowcover depletion curve for each elevation zone. Once the depletion curves for the entire snowmelt period are derived, the daily snowcover values are read-off and used as input to the model equation.

Air temperature expressed in degree days is used in the model as an index of snowmelt. The number of degree days for each 24-hour period is determined by summing the hourly temperatures and dividing by 24 and using 0°C as the base temperature. Temperatures below the freezing point are regarded as 0°C. The degree day figures refer to the 24-hour periods starting at 0600 hours. These temperature data are extrapolated to the hypsometric mean elevations of the respective 500 meter elevation zone by the temperature lapse rate method. The resulting degree days are used for calculating snowmelt. Extrapolation errors would be minimized if the temperature was measured in the basin and near the mean elevation.

Daily precipitation amounts are employed to satisfy the model input requirements. Lacking an acceptable method for extrapolating the precipitation data both horizontally and vertically, data from the closest reporting station are used as zonal inputs as recorded. Again, measurement of precipitation within the basin would greatly aid in the application of the model for snowmelt-runoff simulation.

OTHER SATELLITE DATA WITH APPLICATION TO MAPPING SNOWCOVER

Research has also been conducted to apply data from other satellite systems to snow hydrology. For example, data from the instruments of the Skylab Earth Resources Experiment Package (EREP) have been studied, as well as the hand-

held camera photography taken by the Skylab-4 crewmen as part of the Visual Observations Project (References 28 and 24). Snow mapping was also included as part of the Earth Observations Experiment of the Apollo-Soyuz Test Project (Reference 25). Although not having application for collecting operational snow data, the color photography from the manned space flights has been shown to be very worthwhile for research purposes.

In addition to the use of satellite imagery in the visual portion of the spectrum, the application of data from other spectral regions has also been investigated. Thermal infrared observations have been available routinely for a number of years from meteorological satellites; observations in the near-infrared were made from Skylab; and the Nimbus satellite series has carried microwave sensors since the early 1970's. Studies are continuing to evaluate and develop techniques for use of each of these types of observations.

Thermal Infrared

The NOAA VHRR satellite system has a thermal infrared channel (10.5 to 12 μm) with the same resolution (1 km) as the visible channel. The thermal infrared scanner measures the radiative temperatures of the Earth's surface and cloud tops rather than the reflectances. Therefore, thermal infrared data can be acquired twice each day, whereas the visible imagery can only be acquired during daytime. At high latitudes, the thermal infrared scanner provides the only observations during the winter dark period. Furthermore, the use of thermal infrared has the potential for providing information on the snow surface temperature, a parameter that can be significant with regard to snowmelt prediction.

Accurate delineation of snow boundaries using thermal infrared measurements from satellites depends on detection of small differences in radiative temperature, perhaps only 2° or 3°K. Such temperature differences could be detected for cloud-free views, if all possible "errors" arising from differences in emissivity (ε) of various surfaces, variations in atmospheric attenuation, insufficient resolution of the radiometer, and differences in elevation of terrain were accounted for. Unfortunately, the above "errors" are not known exactly; however, they may be approximated well enough to allow good delineation of snow boundaries and differentiation of some types of snowcovered terrain.

Studies have indicated (Reference 26) that in most instances, snowcover can be delineated in the VHRR thermal data because of its lower temperature, although the thermal gradients associated with snow boundaries are considerably better defined during the spring than during the winter. Caution must be exercised when interpreting infrared data over mountainous terrain, where temperature differences due to variations in elevation may obscure the temperature differences associated with snowcover. An example of VHRR infrared imagery covering the southwestern United States, is shown in Figure 35.

Further studies of the application of thermal infrared measurements to snow hydrology are currently in progress using data from the Heat Capacity Mapping Mission (HCMM), launched in April 1978. The HCMM was the first of a planned series of Applications Explorer Missions (AEM) that involved the placement of
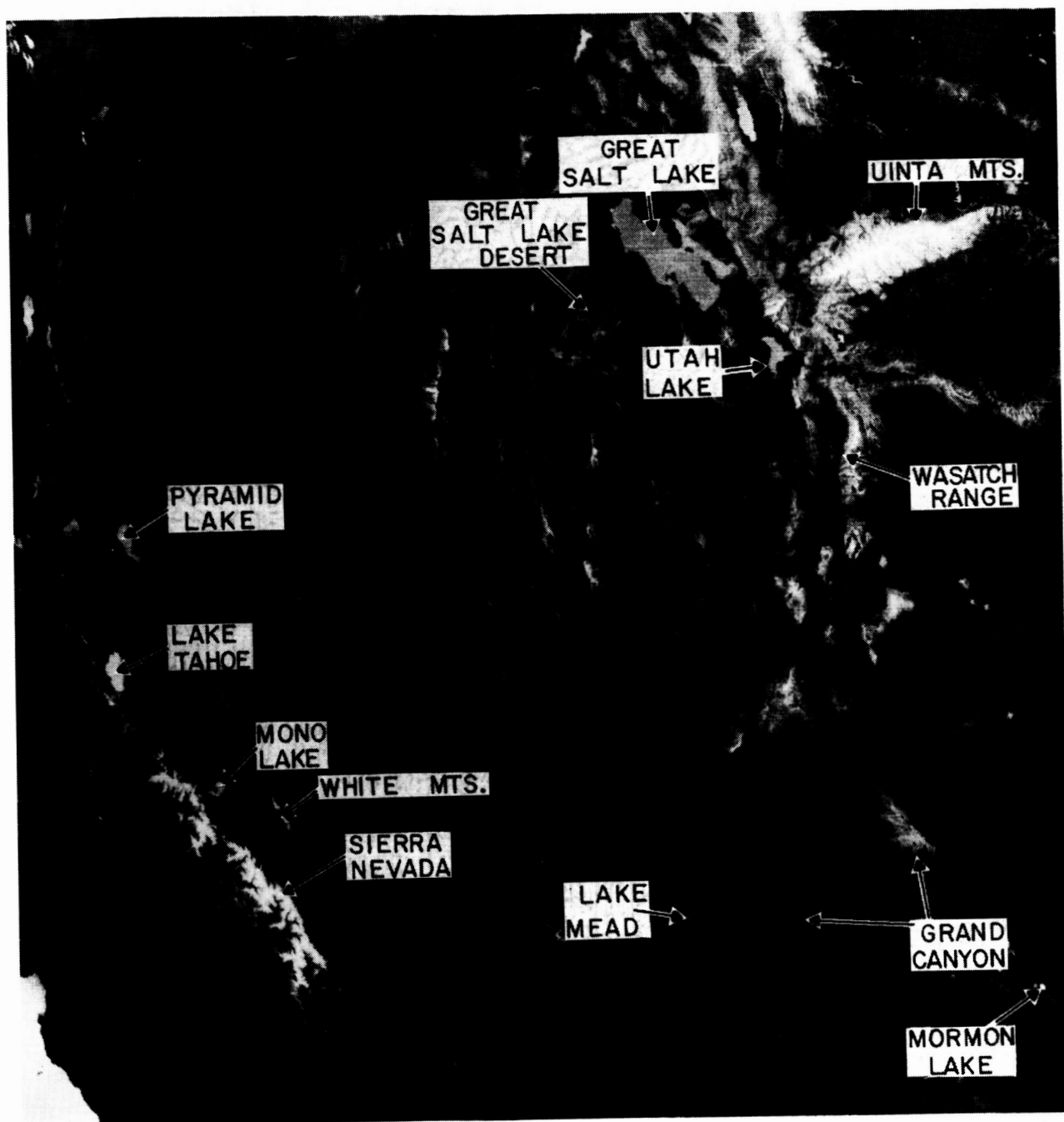
Figure 35.   NOAA-2, DMD (Digital Muirhead Device) processed VHRR infrared
image of 20 June 1973 viewing the southwestern United States.

small spacecraft in special orbits to satisfy mission-unique, data acquisition requirements. The HCMM sensor is a two-channel radiometer similar to the VHRR in its spectral ranges, but with somewhat better resolution (600 m). The primary purpose of the mission is to establish the feasibility of acquiring thermal infrared remote-sensor derived temperature measurements of the Earth's surface within a 12-hour interval of times when the temperature variation is a maximum. Another objective is to apply the day/night temperature difference measurements to the determination of thermal inertia; thermal inertia is the property of material to resist temperature changes as incident energy varies over a daily cycle.

Although the satellite was designed primarily for its geological applications, snow hydrology studies using the HCMM data are being carried out. The main purpose of the studies is to determine whether the thermal measurements from HCMM, and particularly the more precise day/night temperature difference measurements, can be related to snow conditions, such as areas of melting versus non-melting snow. Examples of HCMM visual and thermal infrared imagery are shown in Figures 36a and 36b.

Near-Infrared

As reported by Barnes et al (Reference 26) and Rango et al (Reference 37), snowcover extent measured in the Landsat near-infrared spectral band (MSS-7) is consistently less than that measured in the visible bands because of the decreased reflectance of wet or refrozen snow in the near-infrared. Landsat visible (MSS-5) and near-infrared (MSS-7) images covering the southern Sierra Nevada on 30 June 1973 are shown in Figures 37a and 37b, respectively. The brightest tones in the near-infrared are limited to the highest ridges, whereas in the visible a distinctly larger area appears to be snowcovered. Since a wet snow surface would presumably also have a lower reflectance in the near-infrared (Reference 27), the snow detectable in the MSS-7 image may be the high-elevation dry snow, whereas both the dry and lower elevation wet snow surfaces are visible in the MSS-5 image. A consistent difference in snow extent between MSS-5 and MSS-7 data that is attributed to melting of the snowpack has also been found for drainage basins in the Wind River Range.

In a more thorough examination of the characteristics of snow reflectance in the near-infrared using Skylab Multispectral Scanner (S-192) data, where measurements were made in several near-infrared spectral bands, Barnes and Smallwood (Reference 28) found two potential applications to snow mapping of measurements in the near-infrared spectral region: (1) the use of a near-infrared band in conjunction with a visible band to distinguish automatically between snow and clouds; and (2) the use of one or more near-infrared bands to detect melting snow.

The nearly complete reversal in snow reflectance between the visible and near-infrared bands observed in the S-192 data indicates that in certain portions of the near-infrared, snow surfaces are essentially non-reflective regardless of the condition of the snow. In contrast, the reflectance of clouds (water droplet) displays no decrease in the near-infrared bands. Therefore, a technique combining two spectral bands, one in the visible and one in the near-infrared, can be used to distinguish between snow and clouds. An example of
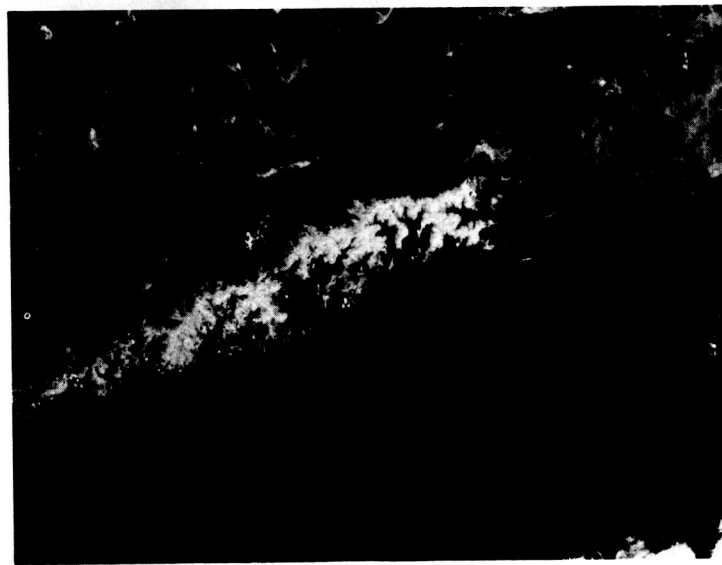
(a)
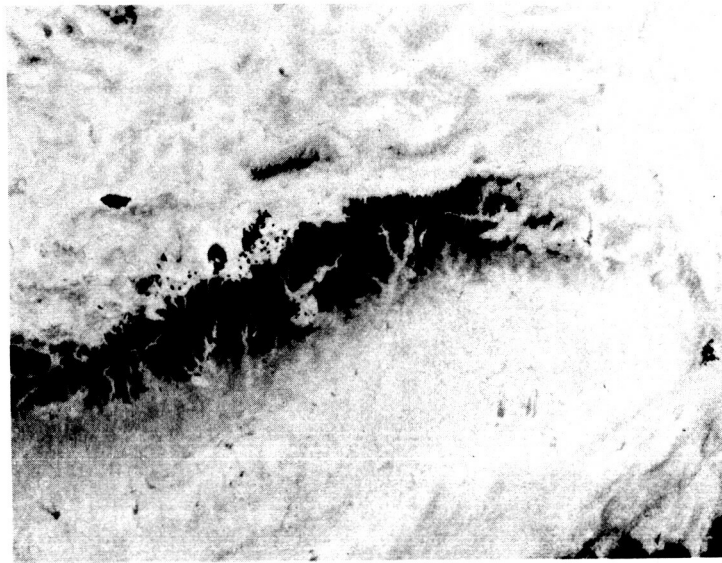
(b)

Figure 36.   Heat Capacity Mapping Mission (HCMM) images viewing the Sierra Nevada, 31 May 1978 (daytime). (a) visible-channel; (b) thermal infrared channel (lower temperatures are darker).

69
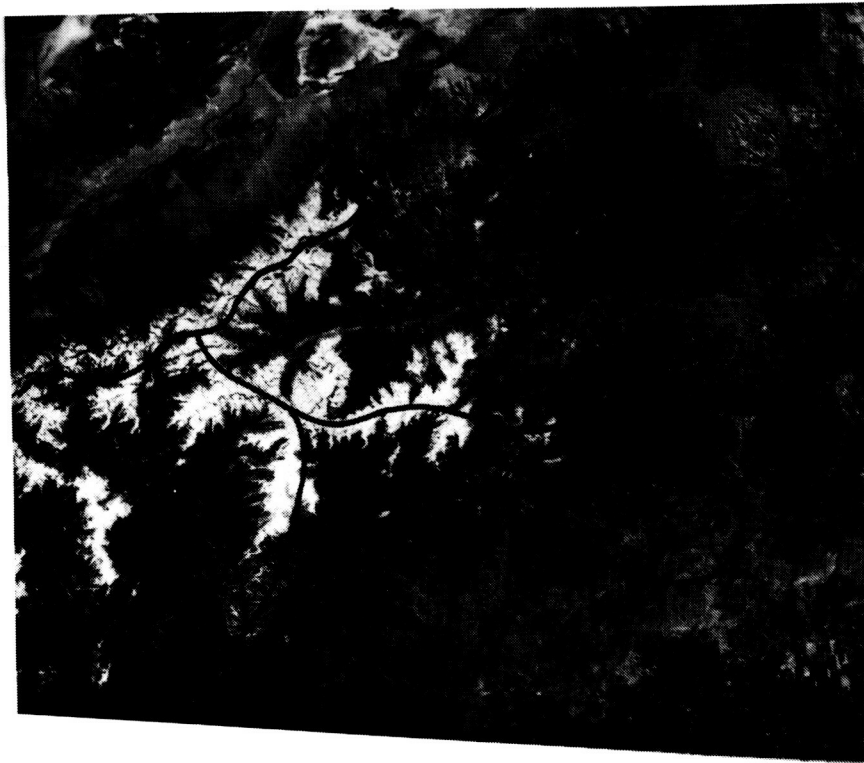
(a)
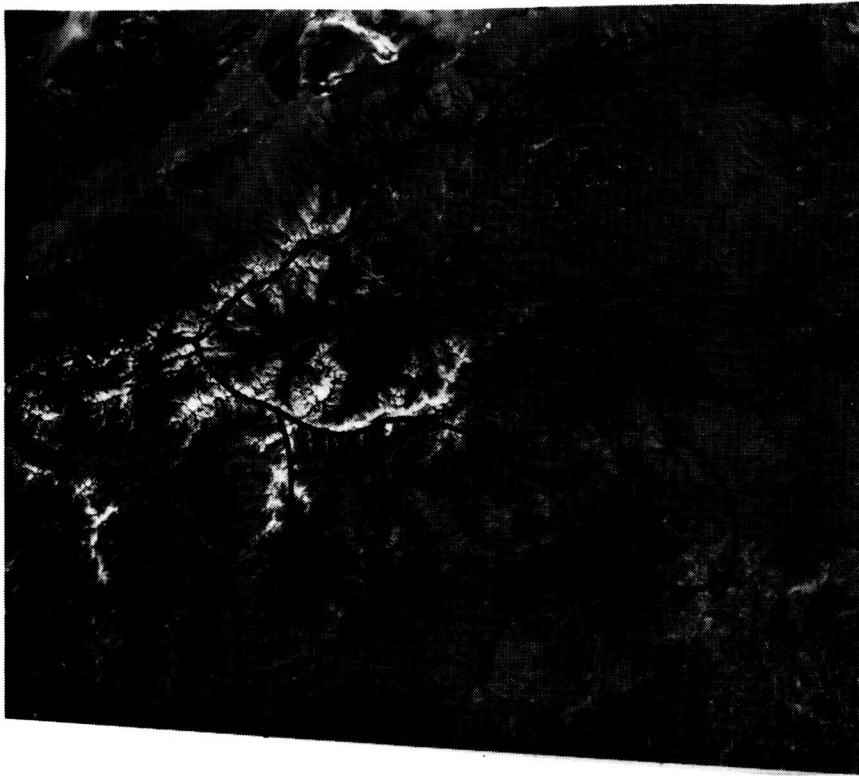
(b)

Figure 37. Landsat-1 MSS-5 (a) and MSS-7 (b) images showing the southern Sierra Nevada, 30 June 1973. River basin boundaries are indicated. Note the apparent lesser snowcover in the near-IR band (MSS-7) as compared to the visible band (MSS-5).

70

this method to distinguish between snow and clouds, is shown in Figure 38a and 38b. It will be possible to test this method further when data become available from the forthcoming DMSP "snow-cloud discriminator", the first operational satellite to carry a near-infrared channel.

The second potential application, that of detecting melting snow, is based on the observed behavior of snow in the intermediate S-192 bands from about Band 7 (0.78 to 0.88 µm) through Band 10 (1.20 to 1.30 µm). For two spring cases, examined, the apparent snow extent decreases gradually from a maximum in the visible (Band 6) to a minimum in Band 11. It was concluded, therefore, that bands in the spectral range from about 0.8 µm to about 1.30 µm, should provide the most information on the condition of the snow surface.

Microwave

Satellite observations in the visible, near-infrared, and thermal infrared portions of the spectrum are all affected by clouds. Microwave sensors, however, provide the capability of viewing the Earth's surface regardless of cloud conditions, so have great potential for snow mapping.

Studies of microwave properties of snow have been carried out for some time using ground-based and aircraft instruments. The microwave radiometers flown in space on the Nimbus satellites have not had sufficient resolution, however, to provide useful snowcover data, especially for mountainous terrain regions. Recently, using data from the improved Nimbus-6 Electrically Scanning Microwave Radiometer (ESMR), the utilization of space-borne microwave radiometers for monitoring snowpack properties has been investigated (Reference 29).

The results of this study show that snow accumulation and depletion at specific locations can be monitored from space by observing related variations in microwave brightness temperatures. Using vertically and horizontally polarized brightness temperatures from the Nimbus-6 ESMR, a discriminant function can be used to separate snow from no-snow areas and map snowcovered area on a continental basis. For dry snow conditions on the Canadian high plains, significant relationships between snow depth or water equivalent and microwave brightness temperature were developed which could permit remote determination of these snow properties after acquisition of a wider range of data. The presence of melt water in the snowpack causes a marked increase in brightness temperature which can be used to predict snowpack priming and timing of runoff. The authors point out that as the resolutions of satellite microwave sensors improve, the application of these results to snow hydrology problems should increase.

SUMMARY OF OPERATIONAL APPLICATIONS OF SATELLITE SNOWCOVER OBSERVATIONS

The current status of the operational application of satellite snowcover observations can best be summarized by reviewing the result of the Snow ASVT. The previously developed techniques for mapping snowcover from satellites were tested during the ASVT, and new techniques were developed. For the first time, procedures to incorporate snowcovered area (SCA) into runoff prediction methods on a quasi-operational basis were tested. Furthermore, each ASVT
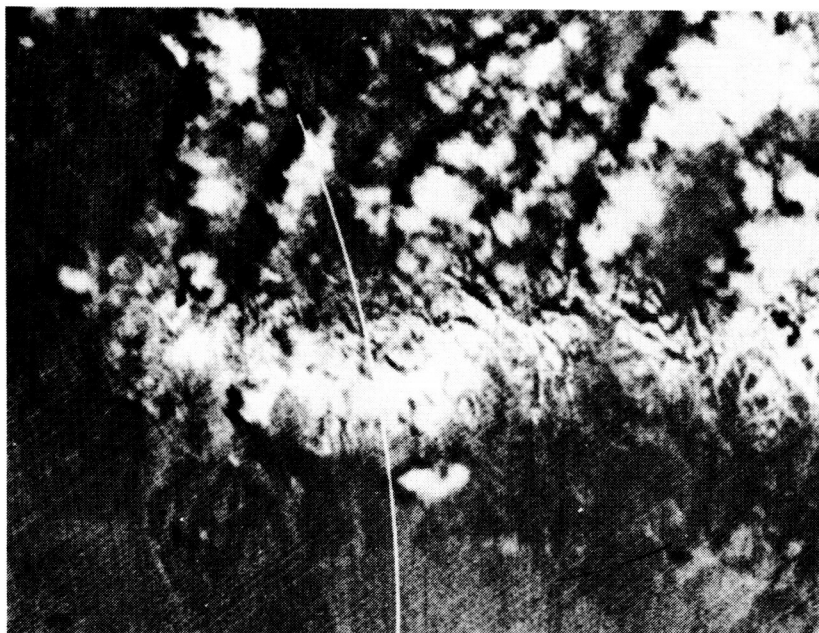
(a) Band 3
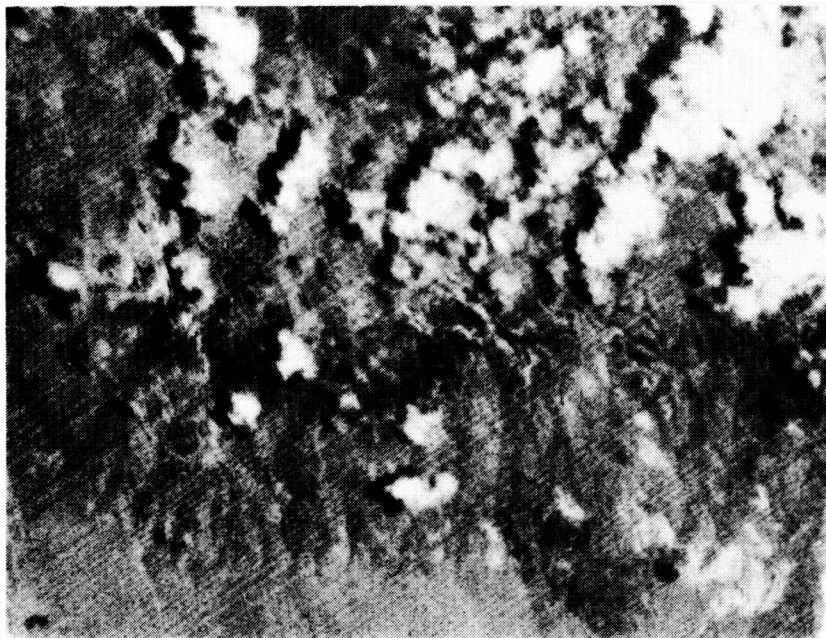
(b) Band 11

Figure 38. Comparison between Skylab S-192 visible and near-infrared data, viewing the White Mountains in California, 3 June 1973; (a) Band 3 (0.52 - 0.56 μm), (b) Band 11 (1.55 - 1.75 μm). Because of the decreased reflectance of the snow, clouds that cannot be detected in Band 3 are distinct in Band 11.

study area had differing characteristics with regard to snowpack, terrain, forest cover, and climate and so had unique problems in applying satellite observations. The principal results of the Snow ASVT and the problems found in working with satellite data in each study area were reported at the Final Workshop on Operational Applications of Satellite Snowcover Observations (References 43, 44, 39 and 45).

Principal Results from the Snow Mapping ASVT

Arizona

The operation of multipurpose reservoirs in semi-arid central Arizona requires timely and dependable snowmelt information. Conventional ground surveys and aerial observations have been used in an attempt to monitor rapidly changing moisture conditions in the Salt-Verde watershed. Since 1974, timely satellite imagery has provided repetitive snowcover observations to assist the managers of the Salt River Project in the operation of their reservoir system.

Results of the snow mapping ASVT in central Arizona indicate that multispectral Landsat imagery permits rapid and accurate mapping of snowcover distributions in small to medium sized watersheds. Low resolution meteorological satellite imagery provides the synoptic daily observations necessary to monitor the large and rapid changes in snowcover. Satellite and microwave telemetry systems were used to furnish near real-time data from streamflow gages and snow monitor sites.

Seasonal runoff predictions by conventional index models and a modified hydrometeorological model (HM) were compared. Significant reductions in the standard-error fractions for seasonal runoff predictions (March - May) were obtained using the HM model. Short-term runoff predictions using snowcover depletion models were also tested. Statistically significant correlations between short-term snowcover depletion rates and runoff rates were determined for selected periods.

California

Results of the California study area indicate that SCA can be determined from Landsat using the Zoom Transfer Scope for watersheds as small as 100 km^2 (40 mi^2), and snowpack depletion may be determined within reasonable limits of accuracy even as the area of snowpack becomes fragmented. Cross-basin plots were developed for the various major basins and subbasins, making it possible to estimate SCA on watersheds that were partly or completely cloud covered from data available on adjacent basins or subbasins. The best results were obtained when mapping was performed using Landsat MSS-5 band positive transparencies at a scale of 1:250,000.

Information on SCA for estimation of both rate and volume of snowmelt runoff was obtained from aircraft and satellite. In many cases, aircraft observations varied more or less consistently from the satellite observations. The aircraft observations in 1978 appeared to show less snowcover than did the satellite observations.

A multiple regression technique was utilized to relate runoff subsequent to the date of forecast to causative parameters. The analysis was predicated on the operational requirement for accurate updating of water supply forecasts throughout the period of snowmelt runoff. The analysis indicated that use of SCA as a parameter in forecasting snowmelt runoff may result in significant improvement for forecasting procedures under certain watershed circumstances.

Simulated mean daily runoff for the Kings River computed as output from a hydrologic model has given results which are entirely acceptable in analysis. In addition, the conceptual model appears to be more consistent with known hydrologic relationships than a previously used snowmelt submodel. Water supply forecasts utilizing SCA as a forecast parameter verified well, while conventional procedures tended to over forecast.

Colorado

In the Colorado snow mapping ASVT study, six methods of mapping snowcover were investigated. The technique that proved to be the most accurate, least expensive, and least time consuming from an operational point of view was the Zoom Transfer Scope.

Two methods of using SCA in forecasting were explored and proved successful. A statistical regression model relates snowcover to seasonal volume flow directly. A computerized simulation model provides short-term and seasonal forecasts using snowcover as an input variable. Results indicating about a ten percent reduction in average forecast error can be realized through use of satellite-derived snowcover in forecast procedures.

Linear regression analysis of six years of snowcover data on six watersheds revealed that snowcover is highly correlated with seasonal streamflow. Combining snow course water equivalent information with Landsat derived snow areal extent data is extremely promising as a forecast tool near the first of May when melt is well underway. Forecasts of the magnitude of the snowmelt peak flow, and to a lesser degree, the date of the peak can be predicted from Landsat snowcover data.

Satellite snowcover data used in combination with SNOTEL and the Subalpine Water Balance Model have been used to develop an extremely flexible system for making continuous short-term streamflow forecasts in the Rio Grande and Arkansas basins. Calibration of the model to five index watersheds of varying sizes (189 to 3,155 km^2) indicate that it is a reliable tool. Operational studies of the Conejos River watershed in 1977 and 1978 have shown that the forecasting system responds well to unforeseen weather changes during a given snowmelt season which can significantly alter the timing and volume of runoff.

Northwest

The results of the Northwest snow mapping ASVT have shown that snowcovered area measured from NOAA and from Landsat satellite data agree within a few percent. The satellite data have provided many more SCA estimates than could be gathered from ground truth data alone, and the satellite-derived SCA data can be used to augment aerial snow survey data.

The interpretation of snowlines from satellite data has been compared with conventional ground truth data and tested in operational streamflow forecasting models. When the satellite SCA data were incorporated into the streamflow Synthesis and Reservoir Regulation (SSARR) model, there was a definite but minor improvement. This improvement was not felt to be statistically significant.

Discussion of Problems

The results of the four-year Snow ASVT have also served to define the problems in the application of satellite data to operational snow mapping. Of course, certain inherent limitations to the use of existing, visible-channel imagery were well-understood before the ASVT was undertaken. It was fully realized that these types of satellite observations cannot provide any information on the depth or water equivalent of mountain snowpacks. The ASVT, therefore, was directed toward an assessment of satellite-derived snowcover extent as a parameter for prediction of snowmelt runoff.

The problems that have been encountered in attaining the avowed goals of the program have been summarized by each study center. Perhaps, the major problem stressed by each study center was the timeliness of the Landsat data. Whereas the snowcover charts derived from the NOAA VHRR imagery were received at the study centers in near real-time, the Landsat data were not always available in time to be useful operationally. For instance, delivery times for standard Landsat imagery averaged nearly four weeks, whereas "Quick-Look" imagery from Canada and from NASA took three to ten days for delivery; with these types of delays, it was impossible to obtain near real-time operational forecasts. Timeliness of data delivery (within 72 hours, at the longest) is extremely critical when runoff forecasts are required.

A high incidence of cloud cover during some periods also resulted in the loss of potentially valuable snowcover estimates for runoff prediction. In Colorado, for example, for the six years of data processed, 40 percent of the available images during the March – June period were unacceptable because of cloud cover. Cloud cover is also an ever present problem in the Pacific Northwest. Portions of the Columbia River Basin are often obscured by clouds during the spring season for extended periods; because cloud cover makes the collection of satellite-derived snowcovered area unreliable in the Northwest, it was concluded at that study center that satellite data cannot be used exclusively for operational purposes at this time. In the California and Arizona areas, cloud cover is less of a problem; in fact, in at least one year, useful data were obtained on nearly every Landsat repeat cycle.

Aside from the cloud problem, the frequency of repeat coverage of Landsat is not adequate, especially for an area with the transient snowpack characteristics of the Arizona study area. With repeat coverage every 18 days, or even every nine days (with two satellites in operation), critical changes in snowcover may be missed completely. In Arizona, therefore, daily satellite coverage, as provided by NOAA VHRR or by GOES, is mandatory.

The characteristics of the sensor systems also present some problems. Although the spatial resolution of the Landsat MSS is completely adequate, the spatial

coverage only allows basins of a certain size to be observed completely on one satellite pass; for example, the entire Salt-Verde Watershed cannot be covered in one Landsat scene. The NOAA VHRR and GOES, on the other hand, both cover broad areas on a single data swath; however, the spatial resolutions of these sensors can be considered marginal for mapping very small watersheds. Moreover, the GOES resolution deteriorates with increasing latitude, so is really useful only for the southernmost areas.

In addition to the inherent limitations of the existing satellite systems, certain problems were also encountered in the interpretation of snowcover. The most significant problems are summarized below; these problems, and methods for handling them, are discussed in detail in earlier sections.

Forest cover effects present a problem for accurate snow mapping in a number of watersheds within each of the study areas. In the Northwest study area, forest cover is a particular problem in determining the snowline in the Dworshak, Libby, and Hungry Horse basins. In these three basins, the mountain crests are above the timberline making it easy to detect the high elevation snowcover; however, it becomes increasingly difficult to determine the snowline on the lower elevation, densely forested slopes. It was noted, for example, that the analysts using NOAA VHRR imagery do not feel confident mapping the Libby Basin until the snowcovered area has dropped to below 50 percent.

Highly reflective bare rock surfaces at higher elevations can also pose a difficulty in accurately distinguishing the snowline. This is particularly true in the Libby and Hungry Horse basins in the Northwest where the rock is light or whitish grey and can be confused with snow late in the melt season. Also, during the severe drought year of 1976-77, portions of the Sierra Nevada in California were snow-free and exposed four to six weeks earlier than normal. Therefore, it was extremely difficult to distinguish snow from exposed reflective rock in the "Quick-Look" Landsat imagery.

In many river basins, a combination of steep slopes and low sun angle can cause shadow problems in the satellite imagery. The reflectance of a north-facing ridge that is totally snowcovered may appear the same as the reflectance of terrain that is completely snow-free. Mountain shadows can be a serious problem particularly in areas such as the Sierra Nevada and the Dworshak, Libby, and Hungry Horse basins in the Northwest study area.

Another source of error discovered in the Colorado snow mapping ASVT, was the obvious difference in judgment as to what constituted snowcover brought about by changes in personnel doing the mapping. Because of this personal bias, some undefined degree of error was built into the areal estimates of snow. Without consistent interpretation from one observer to another, any mapping technique is bound to yield questionable results. To obtain the level of consistency felt necessary for a meaningful analysis, only two interpreters performed final mapping in the Colorado study.

The results of the Snow ASVT have also shown that automated analysis techniques are not practical at this time for operational snow mapping. The analysis of satellite data requires a certain amount of subjectivity and interpreter

experience. Because of this and because of the cost involved, each study center that experimented with automated techniques eventually returned to manual photointerpretation techniques (using the ZTS) for the purposes of the ASVT.

CONCLUSIONS AND OUTLOOK FOR SATELLITE SNOW MAPPING

Snowcover has been mapped from space since the early days of meteorological satellites. To test the application of satellite snowcover as a parameter for runoff prediction on a quasi-operational basis, the Snow ASVT was undertaken in 1974 by NASA, in cooperation with several other agencies. An initial task in the ASVT program was to prepare a handbook of techniques for satellite snow mapping (Reference 1). Now, based on the findings of the four ASVT study centers over the four-year program, this updated handbook of satellite snow mapping and runoff prediction has been prepared. Moreover, because the four ASVT study areas are substantially different in their snowpack, terrain, and forest cover characteristics, the techniques described in this handbook can be readily extrapolated to other geographic locations.

The results of the ASVT as reported by each study center have demonstrated that the areal extent of snowcover as derived from satellite imagery does have potential for improving the timeliness and frequency of hydrologic forecasts in the four study areas. The greatest potential for water supply forecasting is probably in improving forecast accuracy and in expanding forecast services during the period of snowmelt. Problems of transient snowline and uncertainties in future weather conditions are the main reasons that snowcovered area (SCA) appears to offer little in water supply forecast accuracy improvement during the period of snowpack accumulation. The greatest improvement in forecast accuracy with the addition of SCA as a parameter can be expected for basins not already well instrumented.

Existing, visible-channel satellite sensor systems have certain inherent limitations, and there are certain problems in the interpretation of snowcover. A critical problem is the time period for delivery of satellite imagery from the source to the interpreter. Operational experience during the snow mapping ASVT suggests that much more rapid dissemination of available satellite imagery will be required before totally effective use can be made of SCA in operational forecast procedures.

From an operational standpoint, the use of SCA can become restricted when there is considerable cloud cover over mountainous regions for extended periods of time. During these times, neither the Landsat nor the daily NOAA imagery may be suitable for even partial snow mapping of individual watersheds. The experience of the interpreter is extremely valuable in estimating SCA during partial cloud cover conditions. The skill of the analyst is also important when interpreting snowcover in areas of heavy forest cover, mountain shadows, and bare rock terrain. In fact, because subjective decisions must be made by the analyst, and because of the cost involved in computer processing, photointerpretive techniques were found to be the most useful for the purposes of the ASVT. Continued development of automated analysis techniques should certainly be encouraged, however, and offer promise for eventually providing a more efficient means for mapping snowcover from satellites.

77

Because of the demonstrated potential usefulness of satellite-derived SCA data in operational forecasting procedures, each of the ASVT study centers plan to continue to utilize the interpretation of satellite data in conjunction with available ground truth data. As successive years of satellite imagery are accumulated covering a broader range of hydrologic and climatic conditions, forecasts can be expected to improve through use of satellite snow mapping. However, SCA as a forecast parameter does not eliminate the need for other accurate data from conventional sources to define water supply and anticipated runoff. Satellite snow mapping together with improvements in remote hydrometeorological data collection systems, will enable more frequent and accurate forecasts because of increased knowledge of what the conditions are in the major water producing zones above valley floors.

The use of remotely sensed data from spacecraft in activities related to water resources management and studies of the hydrologic cycle is continuing to grow (Reference 46). The observations provided from space have, nevertheless, gained rather slow acceptance because they are still lacking in several respects. For example, they may not have the spatial resolution or spectral resolution necessary for identifying key hydrologic features, and the processing of the high volumes of data provided by remote sensors is often too expensive or too difficult to make their use attractive. Finally, the use of remotely sensed data has often been limited by the speed with which it can be ordered from a data archival center and applied by a water resources manager. Although progress has been made in each of these areas, much remains to be done before the application of satellite data will become "routine" and widespread.

It is believed that a need exists and that there are substantive reasons for making efforts to improve the utility of satellite data. The need arises from the perception that water resources and the associated hydrologic processes must be managed in an increasingly effective manner and must be better understood over larger and larger regions because of expanding populations and increased industrial and agricultural activity. A key reason for attempting to apply better satellite data is that satellites and the associated sensors are particularly suited for providing repetitive, high spatial density, uniform observations over large areas. Future satellite systems or approaches may substantially affect the frequency of use and effective application of satellite data in hydrology and related fields.

A new experimental earth resources monitoring system, Landsat-D, scheduled for launch in late 1981, will offer substantial potential for providing improved information for a wide range of applications. The primary Landsat-D instrument, the thematic mapper, will provide significant technological advantages in spatial resolution, spectral coverage and radiometric resolution. Technological advances, such as that typified by Landsat-D and planned microwave sensors, indicate that significantly greater applications of satellite data to the study of water resources, and particularly snow, are possible.

REFERENCES

1. Barnes, J.C. and C.J. Bowley, 1974: _Handbook of Techniques for Satellite Snow Mapping_, Final Report under Contract No. NAS5-21803 to National Aeronautics & Space Administration/Goddard Space Flight Center, Environmental Research & Technology, Inc., Concord, MA, 95 pp.

2. Fritz, S., 1962: "Snow Surveys from Satellite Meteorology", _Rocket and Satellite Meteorology_, North-Holland Publishing Co., Amsterdam, 419-421.

3. Singer, S.F. and R.W. Popham, 1963: "Non-Meteorological Observations from Weather Satellites", _Astronautics and Aerospace Engineering_, 1(3), 89-92.

4. Tarble, R.D., 1963: "Areal Distribution of Snow as Determined from Satellite Photographs", _Publication No. 65_, _International Association of Scientific Hydrologists_, 373-375.

5. Conover, J.H., 1965: "Notes on the Flora and Snow Cover Distribution Affecting the Appearance of Northeastern United States as Photographed by TIROS Satellite", _Monthly Weather Review_, Vol. 93, No. 10, 646-664.

6. Popham, R.W., A. Flanders and H. Neiss, 1966: "Second Progress Report on Satellite Applications to Snow Hydrology", in _Proceedings of the 23rd Eastern Snow Conference_.

7. Barnes, J.C. and C.J. Bowley, 1968a: "Snow Cover Distributions as Mapped from Satellite Photography", _Water Resources Research_, 4(2), 257-272.

8. Barnes, J.C. and C.J. Bowley, 1968b: _Operational Guide for Mapping Snow Cover from Satellite Photography_, Final Report under Contract E-162-67(N) for NOAA/NESS, Allied Research Associates, Inc., Concord, MA.

9. Barnes, J.C. and C.J. Bowley, 1969: "Satellite Photography for Snow Surveillance in Western Mountains", _Proc. of 37th Western Snow Conference_, Salt Lake City, Utah, April 1969, 34-40.

10. Leaf, C.F., 1969: "Aerial Photographs for Operational Streamflow Forecasting in the Colorado Rockies", _Proc. 37th Western Snow Conference_, Salt Lake City, Utah.

11. Leaf, C.F., 1971: _Areal Snow Cover and Disposition of Snowmelt Runoff in Central Colorado_, USDA Forest Service Research Paper, RM-66 19 pp., Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

12. McClain, E.P., 1973: _Snow Survey from Earth Satellites_, World Meteorological Organization, WMO Pub. No. 353, Geneva, 42 pp.

13. Wiesnet, D.R. and D.F. McGinnis, 1973: "Hydrologic Applications of the NOAA-2 Very High Resolution Radiometer", _Symposium on Remote Sensing and Water Management_, Burlington, Ontario, Canada (June).

14. Wiesnet, D.R., 1974: "The Role of Satellites in Snow and Ice Measurements", Proceedings of Interdisciplinary Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, National Academy of Sciences, Monterey, California, December 2-6, 1973, 447-456.

15. Barnes, J.C., C.J. Bowley and D.A. Simmes, 1974a: The Application of ERTS Imagery to Mapping Snow Cover in the Western United States, Final Report under Contract NAS5-21803, Environmental Research & Technology, Inc., Concord, MA, 77 pp.

16. Barnes, J.C., C.J. Bowley and D.A. Simmes, 1974b: "Snow Studies Using Visible and Infrared Measurements from Earth Satellites", Proceedings of Interdisciplinary Symposium on Advanced Concepts and Techniques in the Study of Snow and Ice Resources, National Academy of Sciences, Monterey, California, December 2-6, 1973, 467-476.

17. McGinnis, D.F., J.A. Pritchard and D.R. Wiesnet, 1975: Snow Depth and Snow Extent Using VHRR Data from the NOAA-2 Satellite, NESS Technical Memorandum, NOAA/National Environmental Satellite Service.

18. Rango, A., 1975a: "Applications of Remote Sensing to Watershed Management", paper presented at Symposium on Watershed Management, American Society of Civil Engineers, August 11-13, 1975, Logan, Utah.

19. Rango, A. (Ed.), 1975b: Proceedings of Workshop on Operational Applications of Satellite Snowcover Observations, August 18-20, 1975, South Lake Tahoe, CA, NASA Publication SP-391, Washington, D.C., 430 pp.

20. Rango, A. (Ed.), 1979: Proceedings of Final Workshop on Operational Applications of Satellite Snowcover Observations (held at Sparks, Nevada, April 16-17, 1979), NASA Goddard Space Flight Center, Greenbelt, MD (in publication).

21. Rango, A. and K.I. Itten, 1976: "Satellite Potentials in Snowcover Monitoring and Runoff Prediction", Nordic Hydrology, 7, 209-230.

22. Rango, A., J.F. Hannaford, R.L. Hall, M. Rosensweig and A.J. Brown, 1979b: "Snowcovered Area Utilization in Runoff Forecasts", Journal of the Hydraulics Division (ASCE), 105 (HYI), 53-66.

23. Haefner, H., K.I. Itten and M. Maurer, 1979: Snow Surveys from Earth Resources Satellites in the Swiss Alps - A Review on Six Years of Research, Remote Sensing Section, Dept. of Geography, University of Zurich (P.O. Box CH-8033, Zurich).

24. Barnes, J.C., C.J. Bowley, J.T. Parr and M.D. Smallwood, 1977: "Snow Mapping Experiment", SKYLAB Explores the Earth, NASA SP-380, NASA Scientific and Technical Information Office, Washington, 191-224.

25. Smallwood, M.D., C.J. Bowley and J.C. Barnes, 1979: <u>Snow Hydrology Studies Utilizing ASTP Photography,</u> Final Report under Contract No. PC6-22331, Environmental Research & Technology, Inc., Concord, MA (in publication by NASA/Johnson Space Center).

26. Barnes, J.C., C.J. Bowley and J.L. Cogan, 1974: <u>Snow Mapping Applications of Thermal Infrared Data from the NOAA Satellite Very High Resolution Radiometer,</u> Final Report under Contract No. 3-35385 to National Environmental Satellite Service, Environmental Research & Technology, Inc., Concord, MA.

27. Strong, A.E., E.P. McClain and D.F. McGinnis, 1971: "Detection of Thawing Snow and Ice Packs through the Combined Use of Visible and Near-Infrared Measurements from Earth Satellites", <u>Monthly Weather Review</u>, 99(11), 828-830.

28. Barnes, J.C. and M.D. Smallwood, 1975: "Synopsis of Current Satellite Snow Mapping Techniques, with Emphasis on Application of Near-Infrared Data", <u>Proc. of Workshop on Operational Applications of Satellite Snowcover Observations</u>, August 18-20, 1975, South Lake Tahoe, CA, NASA Special Publication SP-391, 199-213.

29. Rango, A., A.T.C. Chang and J.L. Foster, 1979a: "The Utilization of Spaceborne Microwave Radiometers for Monitoring Snowpack Properties", <u>Nordic Hydrology 10</u>, No. 1, 25-40.

30. Anderson, H.W., 1963: <u>Managing California's Snow Zone Lands for Water,</u> U. S. Forest Service Research Paper PSW-6, Pacific SW Forest and Range Experiment Station, Berkeley, California.

31. Court, A., 1963: "Snow Cover Relations in the Kings River Basin, California", <u>J. of Geophysical Res.</u>, 68(16), 4751-4761.

32. Foster, J.L. and A. Rango, 1975: "A Method for Improving the Location of the Snowline in Forested Areas Using Satellite Imagery", Document X-910-75-41, NASA Goddard Space Flight Center, Greenbelt, Maryland, 8 pp.

33. Schneider, S. R., 1979: "The NOAA/NESS Program for Operational Snowcover Mapping: Preparing for the 1980's", Preprint, <u>Final Workshop on Operational Applications of Satellite Snowcover Observations</u>, April 16-17, 1979, Sparks, Nevada.

34. Gird, R.S., 1979: "Snow Extent Measurements from Geostationary Satellites Using an Interactive Computer System ", Preprint, <u>Final Workshop on Operational Applications of Satellite Snowcover Observations</u>, April 16-17, 1979, Sparks, Nevada.

35. Tarpley, J.D., S.R. Schneider, E.J. Danaher and G.I. Myers, 1979: "An All-Digital Approach to Snow Mapping Using Geostationary Satellite Data", Preprint, <u>Final Workshop on Operational Applications of Satellite Snowcover Observations,</u> April 16-17, 1979, Sparks, Nevada.

36. Haefner, H., 1979: "Digital Mapping of Mountain Snowcover under European Conditions", Paper presented at Final Workshop on the Operational Applications of Satellite Snowcover Observations, April 16-17, 1979, Sparks, Nevada.

37. Rango, A., V.V. Salomonson and J.L. Foster, 1975: "Employment of Satellite Snowcover Observations for Improving Seasonal Runoff Estimates", Proc. of Workshop on Operational Applications of Satellite Snowcover Observations, August 18-20, 1975, South Lake Tahoe, CA, NASA Special Publication SP-391, 157-174.

38. Thompson, A.G., 1975: "Utilization of Landsat Monitoring Capabilities for Snowcover Depletion Analysis", Proc. of Workshop on Operational Applications of Satellite Snowcover Observations, August 18-20, 1975, South Lake Tahoe, CA, NASA Special Publication SP-391.

39. Shafer, B.A., and C.M. Leaf, 1979: "Landsat Derived Snowcover as an Input Variable for Snowmelt Runoff Forecasting in South Central Colorado," Preprint, Final Workshop on Operational Applications of Satellite Snowcover Observations, April 16-17, 1979, Sparks, Nevada.

40. Leaf, C.F. and G.E. Brink, 1973a: Computer Simulation of Snowmelt Within Colorado Subalpine Watershed, USDA Forest Service, Research Paper RM-99, Fort Collins, Colorado, 22 pp.

41. Leaf, C.F. and G.E. Brink, 1973b: Hydrologic Simulation Model of Colorado Subalpine Forest, USDA Forest Service, Research Paper RM-107, Fort Collins, Colorado, 23 pp.

42. Martinec, J. and A. Rango, 1979: "Discharge Forecasts in Mountain Basins Based on Satellite Snow Cover Mapping", Preprint, Final Workshop on Operational Applications of Satellite Snowcover Observations, April 16-17, 1979, Sparks, Nevada.

43. Schumann, H.H., E. Kirdar and W.L. Warskow, 1979: "Satellite Snowcover and Runoff Monitoring in Central Arizona", Preprint, Final Workshop on Operational Applications of Satellite Snowcover Observations, April 16-17, 1979, Sparks, Nevada.

44. Brown, A.J., J.F. Hannaford and R.H. Hall, 1979: "Application of Snowcovered Area to Runoff Forecasting in Selected Basins of the Sierra Nevada, California", Preprint, Final Workshop on Operational Applications of Satellite Snowcover Observations, April 16-17, 1979, Sparks, Nevada.

45. Dillard, J.P. and C.E. Orwig, 1979: "Use of Satellite Data in Runoff Forecasting in the Heavily Forested, Cloud-Covered Northwest", Preprint, Final Workshop on Operational Applications of Satellite Snowcover Observations, April 16-17, 1979, Sparks, Nevada.

46. Salomonson, V.V. and D.K. Hall, 1979: "A Review of Landsat-D and Other Advanced Systems Relative to Improving the Utility of Space Data and Water-Resources Management", Preprint, <u>Final Workshop on the Operational Applications of Satellite Snowcover Observations,</u> April 16-17, 1979, Sparks, Nevada.

APPENDIX A

LIST OF ACRONYMS

ASVT	Applications Systems Verification and Transfer
BPA	Bonneville Power Administration
CDWR	California Department of Water Resources
COE	Corps of Engineers
EREP	Earth Resources Experiment Package
GOES	Geostationary Operational Environmental Satellite
HCMM	Heat Capacity Mapping Mission
HM	Hydrometeorological Model
MSS	Multispectral Scanner Subsystem (Landsat)
NASA	National Aeronautics & Space Administration
NESS	National Environmental Satellite Service
NOAA	National Oceanographic & Atmospheric Administration
NWS	National Weather Service
OASSO	Operational Applications of Satellite Snowcover Observations
RBV	Return Beam Vidicon (Landsat)
RFC	River Forecast Center
SCA	Snowcovered Area
SCS	Soil Conservation Service
SNOTEL	Snow Telemetry
SRP	Salt River Project
SWB	Subalpine Water Balance (model)
SSARR	Streamflow Synthesis and Reservoir Regulation (model)
TIROS	Television and Infrared Observational Satellite
VHRR	Very High Resolution Radiometer

APPENDIX A

LIST OF ACRONYMS (Continued)

VISSR   Visible and Infrared Spin-Scan Radiometer

ZTS   Zoom Transfer Scope

APPENDIX B

SATELLITE DATA SOURCES AND SOURCES OF
ADDITIONAL SNOW MAPPING ASVT INFORMATION

Information on the availability, formats, and costs of satellite data may be
obtained from the following sources:

NOAA/VHRR and GOES

NOAA, Satellite Data Services Division
World Weather Building, Room 606
Washington, D.C. 20233

Telephone (301) 763-8111

Landsat

EROS Data Center
User Services Unit
Geological Survey
U.S. Department of the Interior
Sioux Falls, South Dakota 57198

Telephone (605) 594-6511

Nimbus and Other NASA Experimental Satellites

National Space Science Data Center
Mail Code 601
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

DMSP

Space Science and Engineering Center
The University of Wisconsin
1225 West Dayton Street
Madison, Wisconsin 53706

Telephone (608) 262-5335

Information on the snow mapping ASVT, including photointerpretation and hydrologic modeling techniques may be obtained from the following sources:

Dr. Albert Rango
Snow ASVT Program Coordinator
Mail Code 913
NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

Telephone (301) 344-5480

Mr. Stanley R. Schneider
NOAA/NESS/Environmental Products Branch
World Weather Building
Room 510, Stop G
Washington, D.C. 20233

Telephone (301) 763-8142

Mr. Herbert H. Schumann
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Suite 1880 Valley Center
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Mr. Jack G. Pardee
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16. Abstract

This handbook has been prepared as one of the reports of the NASA Applications Systems Verification and Transfer (ASVT) program. The purpose of the handbook is to update the various snowcover interpretation techniques, document the snow mapping techniques used in the various ASVT study areas, and describe the ways snowcover data have been applied to runoff prediction. Through documentation in handbook form, the methodology developed in the Snow Mapping ASVT can be applied to other areas.

The material presented in this handbook, to a large extent, is derived from the results produced by the study centers throughout the project. In addition, meetings were held with the personnel directly responsible for the project in each of the four test areas; these meetings were useful for assessing the particular methods adopted by each of the study areas for application of satellite data to improved runoff forecasts. To make the handbook as complete a document as possible, relevant material presented in an earlier handbook, which was prepared as an initial task of the ASVT, is repeated.

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